



OMERE: A Long-Term Observatory of Soil and Water Resources, in Interaction with Agricultural and Land Management in Mediterranean Hilly Catchments

Jérôme Molenat, Damien Raclot, Rim Zitouna, Patrick Andrieux, Guillaume Coulouma, D. Feurer, Olivier Grünberger, Jean-Marie Lamachère, Jean-Stéphane Bailly, Jean-Luc Belotti, et al.

► To cite this version:

Jérôme Molenat, Damien Raclot, Rim Zitouna, Patrick Andrieux, Guillaume Coulouma, et al.. OMERE: A Long-Term Observatory of Soil and Water Resources, in Interaction with Agricultural and Land Management in Mediterranean Hilly Catchments. *Vadose Zone Journal*, 2018, 17 (1), 10.2136/vzj2018.04.0086 . hal-01949323

HAL Id: hal-01949323

<https://hal.science/hal-01949323>

Submitted on 10 Dec 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

Special Section: Hydrological Observatories

Core Ideas

- OMERE is a Mediterranean observatory of two farmed catchments in Tunisia and France.
- Water, contaminant, and erosion fluxes are monitored from plot to catchment scales.
- Soils and land use in relation with agriculture are surveyed.
- Scientific results concern elementary processes and integrated catchment functioning.
- Models were conceived for evaluation of land use and agricultural management scenarios.

J. Molénat, D. Raclot, G. Coulouma, D. Feurer, O. Grunberger, J.M. Lamachère, J.S. Bailly, J.L. Belotti, K. Ben Azzez, A. Biarnès, Y. Blanca, D. Carrière, C. Dagès, A. Dubreuil, J.C. Fabre, D. Fages, C. Floure, F. Garnier, C. Geniez, C. Gomez, R. Hamdi, O. Huttel, F. Jacob, Z. Jenhaoui, P. Lagacherie, Y. Le Bissonnais, R. Moussa, S. Negro, Y. Pépin, L. Prévot, A. Samouelian, G. Trotoux, S. Troiano, F. Vinatier, P. Zante, J. Zrelli, J. Albergel, and M. Voltz. *INRA, IRD, SupAgro, Montpellier, France; R. Zitouna, R. Louati, I. Mekki, and J. Zrelli, INRGREF, Carthage Univ., Tunis, Tunisia; P. Andrieux, ASTRO, INRA, Guadeloupe, France; K. Ben Azzez, M. Ben Younès Louati, R. Hamdi, and Z. Jenhaoui, IRD, Tunis, Tunisia; N. Ben Mechlia and H. Chaabane, INAT, Carthage Univ., Tunis, Tunisia; A. Debabria, DG-ACTA, Ministry of Agriculture, Tunis, Tunisia; X. Louchart, Envilys, Villeneuve-les-Maguelone, France; J.L. Seidel, HydroSciences Montpellier, Univ. Montpellier, CNRS, IRD, Montpellier, France. J. Albergel and M. Voltz are founders of the OMERE observatory. D. Raclot, R. Zitouna, J. Molénat and P. Andrieux are past or current coordinators of the OMERE observatory. D. Raclot, R. Zitouna, P. Andrieux, G. Coulouma, D. Feurer, O. Grunberger, and J.M. Lamachère are past or current site managers of the OMERE observatory. *Corresponding author (jerome.molenat@inra.fr).*

Received 22 Apr. 2018.

Accepted 9 Aug. 2018.

Citation: Molénat, J., D. Raclot, R. Zitouna, P. Andrieux, G. Coulouma, D. Feurer, O. Grunberger, J.M. Lamachère, J.S. Bailly, J.L. Belotti, K. Ben Azzez, N. Ben Mechlia, M. Ben Younès Louati, A. Biarnès, Y. Blanca, D. Carrière, H. Chaabane, C. Dagès, A. Debabria, A. Dubreuil, J.C. Fabre, D. Fages, C. Floure, F. Garnier, C. Geniez, C. Gomez, R. Hamdi, O. Huttel, F. Jacob, Z. Jenhaoui, P. Lagacherie, Y. Le Bissonnais, R. Louati, X. Louchart, I. Mekki, R. Moussa, S. Negro, Y. Pépin, L. Prévot, A. Samouelian, J.L. Seidel, G. Trotoux, S. Troiano, F. Vinatier, P. Zante, J. Zrelli, J. Albergel, and M. Voltz. 2018. OMERE, a long-term observatory of soil and water resources, in interaction with agricultural and land management in Mediterranean hilly catchments. *Vadose Zone J.* 17:180086. doi:10.2136/vzj2018.04.0086

© Soil Science Society of America.
This is an open access article distributed under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

OMERE: A Long-Term Observatory of Soil and Water Resources, in Interaction with Agricultural and Land Management in Mediterranean Hilly Catchments

J. Molénat,* D. Raclot, R. Zitouna, P. Andrieux, G. Coulouma, D. Feurer, O. Grunberger, J.M. Lamachère, J.S. Bailly, J.L. Belotti, K. Ben Azzez, N. Ben Mechlia, M. Ben Younès Louati, A. Biarnès, Y. Blanca, D. Carrière, H. Chaabane, C. Dagès, A. Debabria, A. Dubreuil, J.C. Fabre, D. Fages, C. Floure, F. Garnier, C. Geniez, C. Gomez, R. Hamdi, O. Huttel, F. Jacob, Z. Jenhaoui, P. Lagacherie, Y. Le Bissonnais, R. Louati, X. Louchart, I. Mekki, R. Moussa, S. Negro, Y. Pépin, L. Prévot, A. Samouelian, J.L. Seidel, G. Trotoux, S. Troiano, F. Vinatier, P. Zante, J. Zrelli, J. Albergel, and M. Voltz

To account for the diversity of agricultural and ecosystem situations in hilly Mediterranean areas, the agro-hydrological observatory OMERE (Observatoire Méditerranéen de l'Environnement Rural et de l'Eau) monitors two farmed catchments—one in northern Tunisia and the other in southern France. Mediterranean regions are typified by a highly variable climate, with an alternation of long droughts and intense storms, and by a strong heterogeneity of soil properties, due to a combination of climate, relief, parent materials, sparse vegetation, intense land use, man-made infrastructure (ditches, terraces, etc.), and agricultural activities. In this context, OMERE aims to document the impacts of agricultural and land management on mass fluxes in Mediterranean farmed headwater catchments. The observation strategy is motivated by monitoring water, sediment, and contaminant fluxes and hydrologic and climatic variables at different spatial scales from cultivated plots and landscape elements to the catchment scale. These measurements have been performed at a fine time resolution over a long-term scale and by surveying land use, agricultural practices, and soil surface characteristics. The long-term observation strategy intends to support integrative multidisciplinary research for elucidating the conditions that improve soil and water management and delivery of ecosystem services in a Mediterranean rainfed cultivated context. The observatory has led to scientific insights regarding three scientific objectives: (i) to better understand the fluxes of water, erosion, and contaminants, especially pesticides, and of their natural and anthropogenic drivers on short- and long-term scales; (ii) to analyze the aggregate effects of farming and land management on mass fluxes across scales, from plot to catchment or landscape scales; and (iii) to derive new scenarios for sustainable agricultural management and improved delivery of ecosystem services.

Abbreviations: ERT, electrical resistivity tomography; ET, evapotranspiration; OMERE, Observatoire Méditerranéen de l'Environnement Rural et de l'Eau; SASW, spectral analysis of surface waves; Vis-NIR, visible–near-infrared.

The Mediterranean region is one of the areas in the world that is a hotspot for climate change and, more generally, for global change. Climate change projections predict a significant decrease in winter precipitation and an increase in rainstorms and torrential rains (IPCC, 2014). It is also expected that the population will largely increase from 370 million in 2000 to an estimated 560 million in 2030 (Ludwig et al., 2010). Natural resources and agriculture will be put under large pressure, while there is already

a shortage of these resources and in agricultural production in this area. Arable land is scarce, which leads to the expansion of intensive agriculture in several countries, whether irrigated or rain-fed, toward marginal land that can degrade when too intensively exploited (MediTERRA, 2008). Water resources are basically limited in most Mediterranean ecosystems, given the chronic deficit between rainfall and potential evapotranspiration (ET) and the long drought periods. Water withdrawals for crop irrigation currently amount to a very large proportion of the annual renewable water resources in many Mediterranean countries (Milano et al., 2013). Consequently, the present trends may lead to severe and irreversible environmental damages and, thus, to large social tensions within and between Mediterranean countries.

In this context, long-term observation of the fate of soil and water resources is essential to understanding key processes under way and their interaction with agricultural and land management to better assess the main environmental risks and identify the mitigation levers. It is on these premises that we set up OMERE, a long-term agro-hydrological observatory, situated in the hilly areas of the Mediterranean region, in 2002 (Voltz and Albergel, 2002). The name OMERE is an acronym for Mediterranean Observatory of Rural Environment and Water (Observatoire Méditerranéen de l'Environnement Rural et de l'Eau, in French). It was part of an initiative of the French Ministry of Research that launched a call for funding Environmental Research Observatories (French acronym ORE, for Observatoire de Recherche en Environnement) to provide high-quality observational data for studying the functioning of continental systems and their long-term dynamics. The observatory OMERE filled the lack of long-term environmental observatories in the Mediterranean region. To illustrate this point, one can note that at the landscape or regional scales, only five Mediterranean agricultural observatories are registered on the Long-Term Ecosystem Research sites map (<https://data.lter-europe.net/deims/site/list>), two of them being the OMERE observatory.

To take into account the diversity of agricultural and ecosystem situations in the hilly Mediterranean areas, OMERE monitors two farmed catchments—one in Cap Bon Peninsula in Tunisia, and the other in the south of France. Both sites have been monitored since the 1990s and represent two typical Mediterranean land uses, namely, (i) the combination of cereal crops and rangelands and (ii) vineyard monoculture. The OMERE observatory is co-managed by five research institutes: Institut National de la Recherche Agronomique (INRA), Institut de Recherche pour le Développement (IRD), and Centre National de la Recherche Scientifique (CNRS) in France, and Institut National Agronomique de Tunisie (INAT) and Institut National du Génie Rural, des Eaux et Forêts (INRGREF) in Tunisia. In 2011, OMERE took part in the creation of the French network of drainage basins, Réseau des Bassins Versants (RBV, <http://portailrbv.sedoo.fr/>), and now the Observatoire de la Zone Critique, Applications et Recherches (OZCAR) infrastructure for observing the critical zone for the long term (Gaillardet et al., 2018). Furthermore, OMERE has taken part in international

research initiatives such as the Surfaces et Interfaces Continentales en Méditerranée (SICMED) project (Voltz et al., 2018) and the Soil Transformations in European Catchments (SoiLTrEC) project (Menon et al., 2014).

Here, we describe the motivation and science questions that support the monitoring efforts of OMERE and present the characteristics and monitoring design of both OMERE sites, as well as an overview of the obtained results. Today, 20 yr of results provide very positive scientific paybacks. Finally, some lessons and perspectives that emerged, in our opinion, from the long-term monitoring experience are emphasized.

Motivation and Science Questions

In addition to the environmental challenges described above, Mediterranean landscapes exhibit strong intrinsic specifications that make them a suitable model for studying global change effects.

A major characteristic of Mediterranean landscapes is that they are the fruit of millennia of anthropogenic cultivation. Therefore, they are an example of intensive land management that has often shaped the landscapes through digging ditches, building hilly reservoirs, forming terraces for preventing or limiting water erosion and surface runoff, or intensive farming practices that exploited almost every piece of land. Moreover, they offer a diversity of situations for comparison. Today, for example, strong social dynamics imply the coexistence of agricultural intensification in favorable places with agricultural decline in marginal lands (de Franchis and Ibanez, 2003; García-Ruiz et al., 2013). Both OMERE sites include such diversity.

The characteristics of Mediterranean climate, namely, its chronic deficit of water, long periods of drought, very large inter-annual variations, and high frequency of intense, sometimes devastating, storms, may also be seen as an experimental model for many temperate countries that will experience climate change. Examining strategies developed by Mediterranean ecosystems and farmers to adapt to this highly variable climate may offer very useful lessons for mitigating climate change.

Eventually, Mediterranean soils that result from a unique combination of climate, relief, heterogeneous parent materials, sparse vegetation, and intense land use also add to the exemplary character of the Mediterranean area. Soils are organized in a complex pattern across short distances, often associating uphill shallow and skeletal soils with downhill deep soils, formed from a colluvium of eroded material. They are generally poor in organic matter and prone to erosion. With the predicted increase in temperature, droughts, and intense storms, it is expected that soil losses may accelerate, and soil C stocks may be depleted (Lagacherie et al., 2018). The overall vulnerability of Mediterranean soils and their high spatial variability is thus an opportunity for evaluating sustainable management practices, both at the plot and landscape scale.

In this context, OMERE observatory aims to document the impact of agricultural and land management on mass fluxes in typical farmed headwater catchments of the Mediterranean region.

Its long-term observation strategy intends to support integrative multidisciplinary research for elucidating the conditions for improved soil and water management and delivery of ecosystem services. Accordingly, the researchers that take advantage of the facilities provided by OMERE address a large number of scientific issues that can be grouped according to three broad objectives. We describe these objectives below and how they lead to specific research questions, in relation to the particular characteristics and processes of the Mediterranean farmed areas.

A first objective is to estimate the fluxes of water, erosion, and contaminants and to identify their natural and anthropogenic drivers on short- and long-term scales. This very basic objective, common to most hydrological observatories, requires, in the case of OMERE, the tackling of specific research questions related to the particular characteristics and processes that occur in Mediterranean hydrosystems. Among them are the study of (i) the influence of uneven and intense runoff events and of long periods of drought on the hydrological cycle and on the dynamics of soil and water contamination by pesticides; (ii) the spatiotemporal variations in infiltration and runoff partitioning and in erosion in relation to soil types and soil tillage; and (iii) the influence of slopes and of row cropping, such as in vineyards and orchards, on ET fluxes.

A second objective is to elucidate the aggregate effects of farming and land management on the mass fluxes across scales, from plot to catchment or landscape scales. It is expected that these effects are very significant in regard to the general fate of soil and water resources, and in turn, good management may mitigate the negative effects of global change. Accordingly, the influence of many natural or man-made features is studied at OMERE. Among them are soil tillage, plot and catchment water harvesting techniques, ditch networks, and terraces that all correspond to typical management activities in Mediterranean farmed areas.

A third objective is to derive new scenarios for a sustainable agricultural management and improved delivery of ecosystem services by Mediterranean farmed landscapes (e.g., agricultural biomass production, water production, erosion prevention, flood regulation, and water contamination regulation). For this aim, spatially distributed modeling approaches for simulating water, sediment, and contaminant fluxes at plot and catchment scales are developed and evaluated. They benefit from large, long-term monitoring datasets and detailed processes analysis, prone to facilitate model design, calibration, and validation. Moreover, basic knowledge and multi-decadal time series observations sustain applied research, dedicated to diagnostic tools for agro-environmental engineering of cultivated landscapes.

Motivation of OMERE goes largely beyond its strict scientific interests. Equipped sites offer very good support for educational purposes and capacity building. Each year, many students and professionals in hydrology, agronomy, soil sciences, and related topics visit the sites, become familiar with monitoring techniques, observed processes, and farming systems, or have tutorials in the field. Moreover, since OMERE is binational, it enhances

cooperation between the northern and southern shores of the Mediterranean Sea and helps to build some pieces of common culture and understanding, which is valuable in the present times.

Catchment Characteristics

The experimental catchments are located on both sides of the Mediterranean Sea. The Roujan catchment is 60 km west of Montpellier (43°30' N, 3°19' E) in the south of France, and the Kamech catchment (36°87' N, 10°87' E) is located within the Cap Bon Peninsula in the north of Tunisia (Fig. 1). The main features of both catchments are given in Table 1. The climate is rather similar for the two sites. Kamech and Roujan are characterized by a similar annual rainfall (25-yr means of 645 and 628 mm for Kamech and Roujan, respectively), unevenly distributed throughout the year. The major rainfall occurs in spring and autumn for the French site, whereas the end of spring and the summer are systematically dry periods for the Tunisian site. The mean maximal temperature is the same at both sites (~15°C in January and 30°C in July to August). However, the minimal temperature is different; it is always 5°C lower in Roujan and without frost days in Kamech. The two catchments present typical Mediterranean hydrological responses (Fig. 2), with annual stream runoff depending mainly on annual rainfall and with the occurrence of extreme runoff events (a maximum annual specific runoff of 520 mm observed in Roujan in 1996). The annual reference ET (ET_0) is 1109 and 1366 mm in Roujan and Kamech, respectively. Every year, the two catchments are characterized by a threshold cumulative rainfall of ~450 mm, before marked stream runoff starts. This large rainfall threshold can be explained by the ET that leads to soil drying from spring to fall, by rainfall infiltration due to topsoil cracks at the end of the summer in Kamech, and by runoff infiltration through ditch bottoms, due the dense network of ditches in Roujan.

The substratum of the two catchments belongs mainly to the Miocene marine deposits (Fig. 3). However, the nature is different. In Roujan, the calcareous loose sandstone with centimetric laminations and intercalations of loamy clay material is covered by lacustrine limestone, which constitutes the bedrock of the catchment. In Kamech, the bedrock corresponds to the slightly calcareous laminated mudstone, with intercalations of hard sandstone. The soil along the hillslopes is directly developed over and from the Miocene deposits and is representative of the main Mediterranean soils (European Soil Data Centre, 2014). The soil depends on the nature of the deposits and on the position within the slope. The main difference is observed in the highly clayed soils in Kamech and calcareous silty soils in Roujan (Table 1). Following International Union of Soil Sciences classification, soils are Cambisols, Regosols, and Calcisols in both catchments, with the addition of Vertisols in Kamech (IUSS Working Group WRB, 2014). The soil depends mainly on the slope. Along the hillslope, soil depth increases from upslope to downslope, with changes in soil texture in relation to the colluvial deposits. Temporary and permanent shallow groundwaters are present along the hillslopes

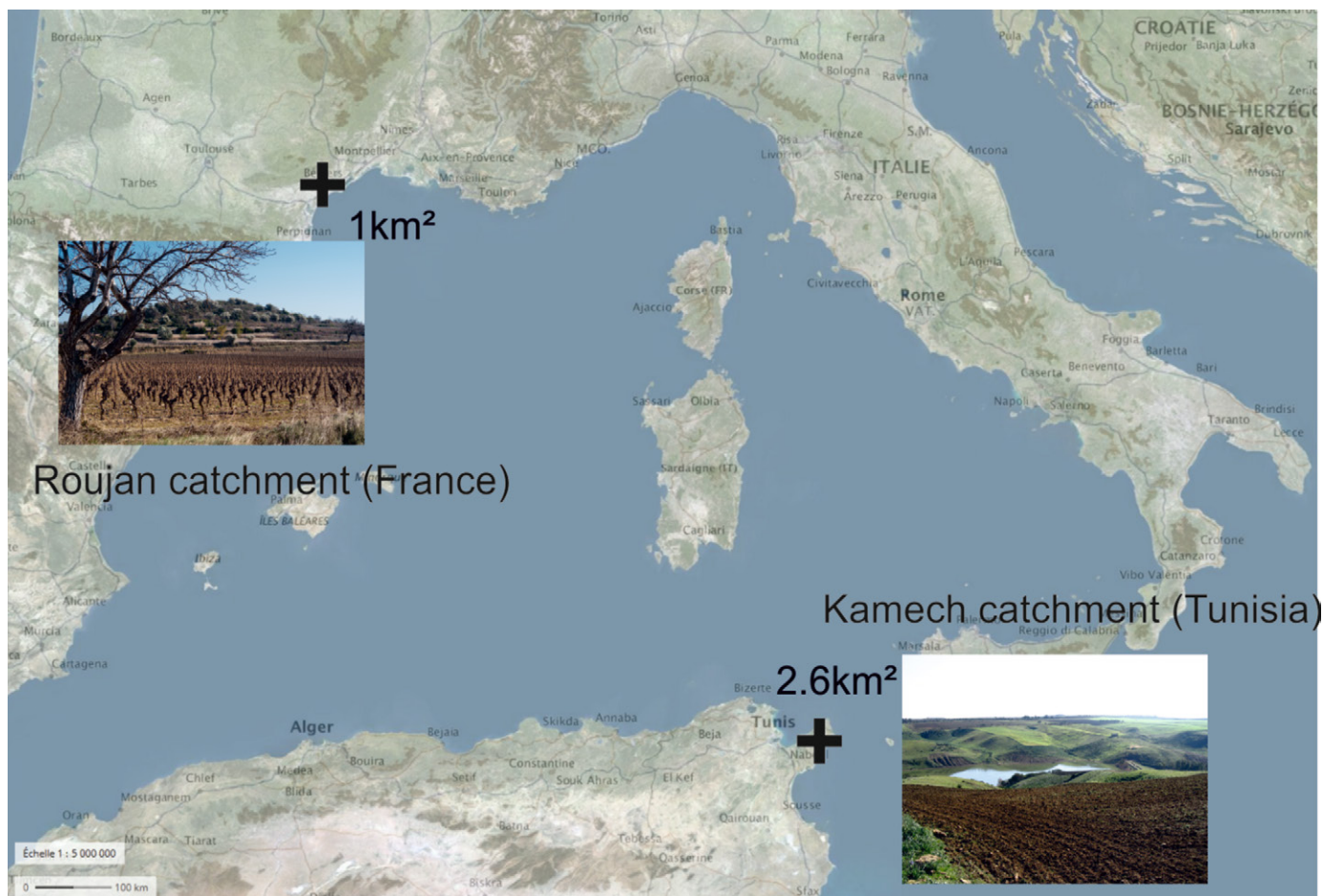


Fig. 1. Locations of Roujan and Kamech experimental catchments.

and in the bottom lands of the two catchments. The unweathered mudstone in Kamech (between 2 and 6 m deep) and the deep loamy clay marine deposits in Roujan (between 4 and 7 m deep) constitute the lower bed of shallow groundwater.

More than 80% of the catchment area is covered by croplands. There are sharp contrasts in landscape between the steep slope areas with human terraces or rangelands (i.e., west to east for Roujan, and northwest to southeast for Kamech) and the rest of the catchment, especially the glacia in the Roujan catchment.

Table 1. Main features of the Observatoire Méditerranéen de l'Environnement Rural et de l'Eau (OMERE) catchments.

| Property | Roujan | Kamech |
|--|-----------------------|--|
| Area, km ² | 0.92 | 2.63 |
| Slope (quartiles), % | 0, 3, 6, 11, 30 | 0, 6, 11, 18, 30 |
| Clay content (range), % | 5–37 | 12–67 |
| Pebbles (range), % | 0–58 | 0–16 |
| Soil calcium carbonate (range), g kg ⁻¹ | 4–479 | 2–199 |
| Soil organic matter (range), % | 0.4–2.6 | 0.3–2.0 |
| Soil thickness (range), m | 0–4.5 | 0–2.5 |
| Land use | vineyards and cereals | cereals, legumes, and degraded rangeland |

The gentle slopes are covered mostly by vineyards in Roujan, with some orchards in the bottom lands. Remaining parts are covered by shrubs and low trees. Kamech is mainly covered by cereals and leguminous crops. Remaining parts are covered by

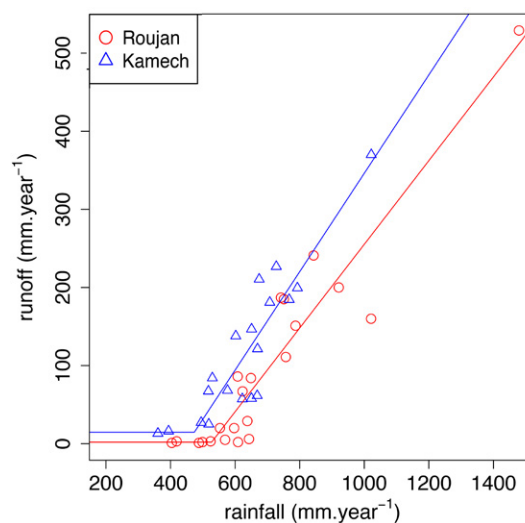


Fig. 2. Relationship between annual rainfall and annual stream runoff in the two sites. The period ranges from 1993 to 2015 in Roujan and from 1995 to 2013 in Kamech (adapted from Voltz et al., 2016).

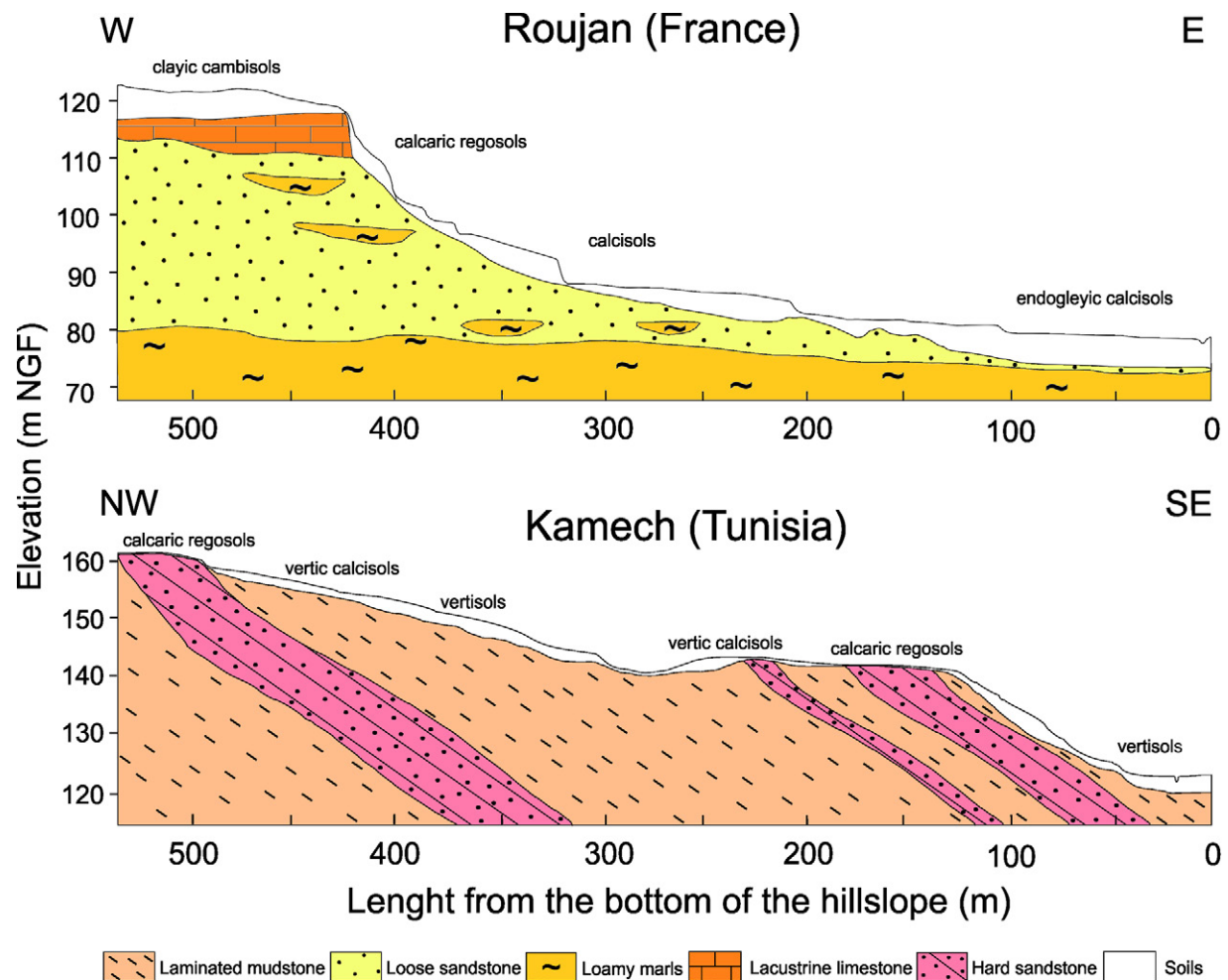


Fig. 3. Geological cross-sections of the main hillslope of the two catchments. The main soils are described according to the World Reference Base classification (IUSS Working Group WRB, 2014).

degraded rangelands and dwellings. Agricultural practices are different between Roujan and Kamech. Intensive viticulture in the Languedoc area has tended to decrease with lower production since the middle of the past century, whereas the use of mechanization and chemicals has been increasing in Kamech.

The two sites have been dedicated to agriculture for several thousand years and currently present anthropogenic features aiming to control runoff, to decrease erosion damages, and to preserve soils and water (Fig. 4). There are >10 km of ditches in Roujan, around the vineyard fields. A dam was built at the Kamech outlet in 1994 for reducing downstream siltation and for water harvesting. These anthropogenic features highly affect the hydrological behavior of both catchments.

Basic Long-Term Observations

Observation Strategy

To meet its objective of observing hydrological processes related to agricultural activities in hilly rural Mediterranean areas, OMERE developed an observation strategy, allowing for the high spatial and temporal variabilities of different

observed variables to be considered. As we aimed to study how farming and land management at local scales control water and soil resources, the observation infrastructure was designed to monitor fluxes at nested scales, from the plot (i.e., the farm field) to the catchment scales (Fig. 5). More generally, most observations are recorded through a network of sensors, which allows the description of the spatial heterogeneities within the catchments. Table 2 details the hydrometeorological variables monitored in both OMERE sites.

In accordance with the high temporal variability of hydrological and meteorological processes in the Mediterranean region, the observations are performed at high frequency—typically 5-min intervals or shorter. As the observatory is dedicated to the study of land cover and agricultural practices as drivers of soil and water resources, surveys of land cover and agricultural practices are also a key element of the observation strategy.

Meteorological Data

Eleven daily-read cumulative rain gauges and four automatic tipping-bucket rain gauges were installed to monitor rainfall intensity and its spatial pattern. Automatic rain gauges provide instantaneous data. Quality control is performed by comparing

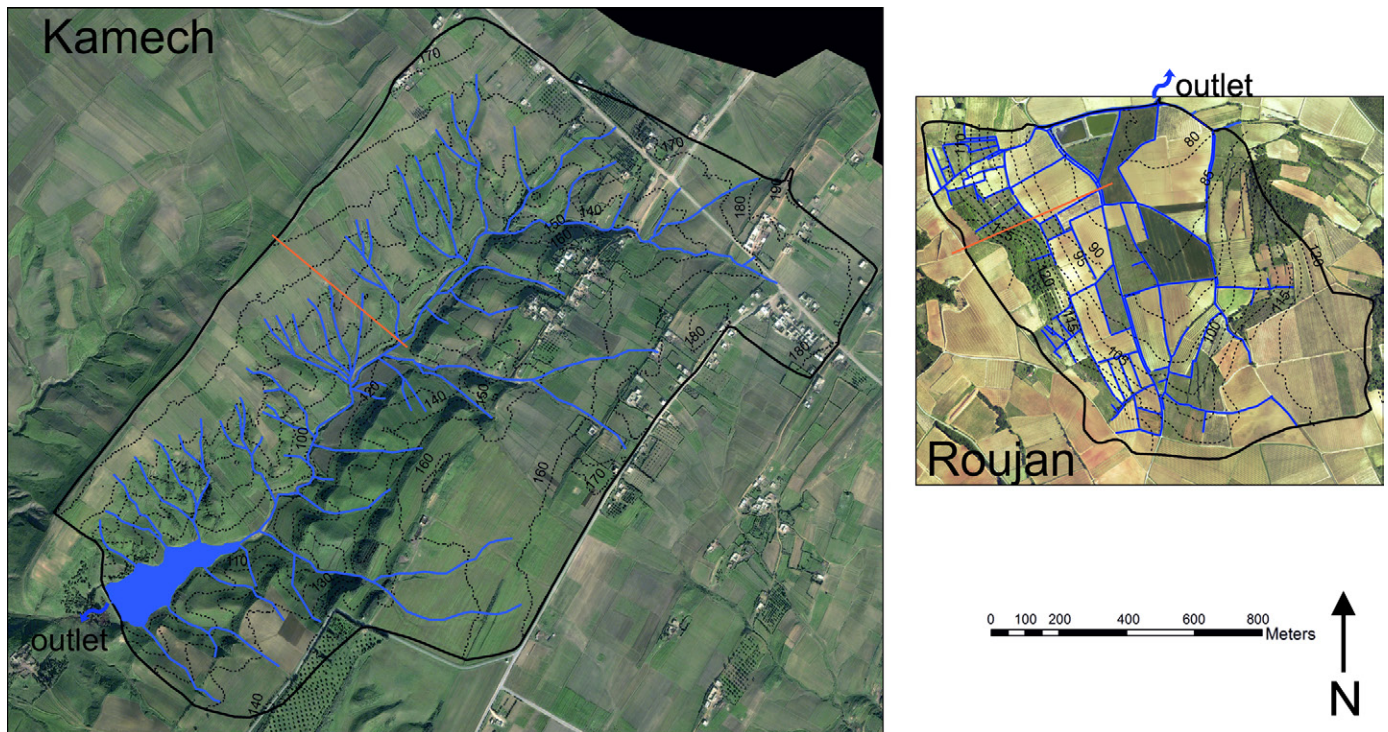


Fig. 4. Aerial maps of Roujan and Kamech catchments (same scale). The catchment boundaries are depicted by thick black lines, the elevation curves are thin black lines, and the drainage system, including a small reservoir in the Kamech catchment, is drawn with blue lines. The thin red lines correspond to the geological cross-sections of Fig. 3.

daily reads of cumulative rain gauges and cumulative daily records with automatic rain gauges. Rainfall has been monitored since 1992 in Roujan and 1994 in Kamech.

A weather station records the following atmospheric parameters at each site: air temperature and humidity, wind speed and direction at 2 m above ground level, and global radiation at 1 m above ground level. In addition, free water evaporation is measured on a

daily basis on the Tunisian test site, with a sunken Colorado 1-m² evaporation pan.

Surface Water

Water levels in the hydrographic network are measured with hydrometric stations. The stations are placed strategically to obtain water flow data for studying the scale effects from field to

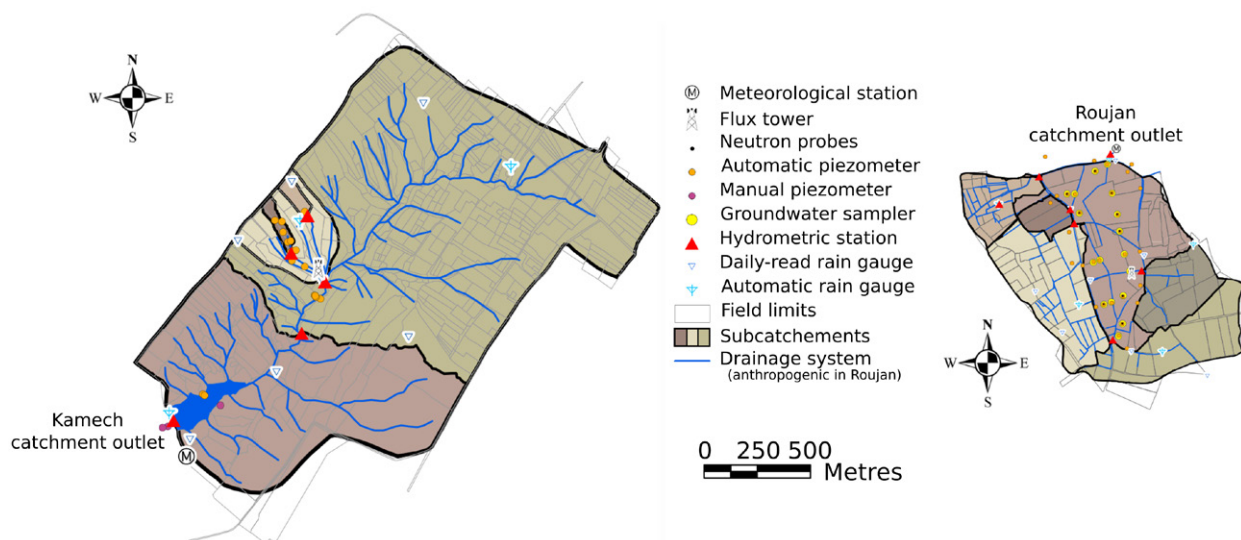


Fig. 5. The Observatoire Méditerranéen de l'Environnement Rural et de l'Eau (OMERE) hydrometeorological monitoring infrastructure (see details in Table 2). The different surface colors indicate the subcatchments delineated from hydrometric stations. In the Roujan catchment, the drainage system contains mainly anthropogenic ditches, fed by surface runoff. In the Kamech catchment, the drainage system contains mainly a natural wadi network.

Table 2. Recorded hydrometeorological variables and sensors used at Observatoire Méditerranéen de l'Environnement Rural et de l'Eau (OMERE) sites.

| Variables | Scale | | | Measured since | Acquisition | |
|-----------------------------------|----------------------------|-----------------------|----------------|---------------------------------------|---|---|
| | Field plot/ distributed | Hillslope/ network | Catchment | | Sensors | Automatic or manual (frequency)† |
| Meteorology | | | | | | |
| Rainfall (intensity) | X | X | X | 1992 ^R /1994 ^{K†} | 400-cm ² 0.5-mm tipping-bucket Précis Mécanique rain gauges | A (instantaneous) |
| Rainfall (total) | X | X | X | 1992 ^R /1994 ^K | 400-cm ² Précis Mécanique and Hydreka rain gauges | M (daily) |
| Rainwater chemistry | X | X | | 2004 ^R /2016 ^K | CIMEL rain sampler and manual sampling | A (event) and M (daily) |
| Wind speed | | | X | 1992 ^R /1999 ^K | A100R ^K (Vector) and CIMEL-CE155 ^R anemometers | A (30 ^K and 60 min ^R daily) |
| Wind direction | | | X | 1992 ^R /1999 ^K | W200P ^K (Vector) and CES157 ^R (Cimel) wind vanes | |
| Air temperature and humidity | | | X | 1992 ^R /1999 ^K | HMP45 ^K (Vaisala) and CES185-191 ^R (Cimel) thermohygrometers | |
| Global radiation | | | X | 1992 ^R /1999 ^K | SP1110 ^K (Skye) and CMP6 ^R (Kipp & Zonen) pyranometers | |
| Evaporation ^K | | | X ^K | 1995 ^K | sunken Colorado pan | M (daily) |
| Land surface fluxes | | | | | | |
| Actual evapotranspiration | | X | | 2005 ^R /2010 ^K | CSAT ^K (Campbell) and 81000 ^R (Young) three-dimensional sonic anemometers, Li7500 (LI-COR) H ₂ O/CO ₂ analyzers | A (30–60 min) |
| Surface water fluxes | | | | | | |
| Discharge (water level) | X | X | X | 1993 ^R /1994 ^K | CS451 (Campbell) and ELSYDE SPI pressure sensor, SEROSI nilometer | A (1 min) |
| Sediment load | X | X | X | 1994 ^R /2004 ^K | OBS500 turbidimeter (Campbell), SD900P 24-bottle samplers (Sigma) and homemade cumulative sampler, manual sampling during floods | A and M (5 min, event) |
| Sediment budget ^K | | | X ^K | 1994 ^K | field surveyed Kamech's lake bathymetry | M (biennial) |
| Major cations and anions | X | X | X | 1994 ^R /2009 ^K | SD900P 24-bottle samplers (Sigma) and manual sampling | A and M (event) |
| Pesticides | X | X | X | 1997 ^R /2017 ^K | SD900P 24-bottle samplers (Sigma), manual sampling | A and M (1-min, event) |
| Groundwater | | | | | | |
| Water table level and temperature | X | X | | 1993 ^R /2007 ^K | pressure sensor (Keller & Druck, Diver, US 517, LevelTroll) | A (5 min ^K , 60 min ^R) |
| | X | X | | 1992 ^R /2007 ^K | manual measures | M (weekly) |
| Groundwater conductivity | X | X | | 2004 ^R /2007 ^K | CTD (Diver) | A and M (event) |
| Major cations and anions | X | X | | 2004 ^R /2007 ^K | SD900P 24-bottle samplers (Sigma), manual sampling | M (event) |
| Soil moisture | | | | | | |
| Water content | X ^R | X ^R | | 2005 ^R | neutron probes | M (monthly) |
| | X ^R | | | 2014 ^R | SoilNet network with SPADE (Sceme) soil moisture sensors | A (30 min) |

† A, automatic acquisition; M, manual acquisition.

† Superscript K indicates the Kamech site, and superscript R indicates the Roujan site.

catchment scales, as well as to understand the impacts of the landscape and soil structures on water flow, such as gullies in Kamech and ditches in Roujan. In total, a network of hydrometric stations (five in Kamech and seven in Roujan) equipped with flumes were installed. Water levels in Venturi or U-shaped concrete flumes are continuously recorded, as well as water electrical conductivity. For that purpose, a flat V-weir was built in hydrometric stations with U-shaped flumes. Stage-discharge curves were obtained with field surveys for a large range of discharges.

Groundwater

The water table is measured through piezometer networks, which were designed to describe spatial and temporal variabilities of the water table and to understand groundwater–stream exchanges. The piezometers are equipped with automatic pressure sensors, recording water level and temperature at sub-hourly time steps. Depending on the catchments, one to four piezometers are equipped with an automatic water electrical conductivity sensor. Manual measurements of the water level

are performed monthly to check for and correct potential pressure sensor drifts.

Soil Moisture

In the Roujan catchment, nine neutron probe access tubes were installed in 2004 to monitor soil moisture in the rooting zone, mostly in vineyards. They were installed in the vicinity of existing piezometers to obtain deep water content profiles. The accessible depths vary between 2.2 and 3.8 m, depending on tube locations, and measurements are performed at 0.2- to 0.4-m depth increments. Measurements are performed approximately every month, with the frequency varying according to rainfall events. To obtain a higher time resolution, a SoilNet wireless network (Bogena et al., 2010) of five soil moisture profiles was installed in 2014. Each profile includes six temperature and soil moisture sensors (ring oscillators) located at approximate depths of 0.1, 0.3, 0.6, 1.0, 1.5, and 2.0 m. Data are collected and transmitted every 30 min. In Kamech, soil moisture has been measured less continuously; the main campaigns were conducted in 1999–2000 and 2012–2013, with a neutron probe or from gravimetric samples (Mekki et al., 2018).

Land Surface Fluxes

Eddy covariance techniques are routinely used to measure fluxes between surface and atmosphere, mainly the latent heat flux or ET. Similar flux towers were installed near the centers of the Roujan and Kamech catchments in 2005 and 2010, respectively. Both towers are equipped with fast response (20 Hz) sensors, a three-dimensional sonic anemometer and an open-path H₂O/CO₂ analyzer. They differ by the height of the sensors, which are 6.2 and 9.6 m above ground level for Roujan and Kamech, respectively, leading to a smaller average footprint (12 ha) in Roujan than in Kamech (19 ha). The sensible and latent heat fluxes are routinely calculated hourly, quality checked using standard tests, and then aggregated at a daily time step after the gap-filling of missing or rejected data to obtain continuous chronicles of ET.

Water Chemistry and Contaminants

For each runoff event occurring at both sites, samples of water are collected, using either automatic 24-bottle samplers or cumulated automatic samplers, in each of the hydrometric stations. Additionally, the electrical conductivity and the major anions and cations are analyzed.

The dynamics of pesticides, mainly herbicides, have been monitored since the beginning of the observatory, using the nested network of hydrometric stations in Roujan. The monitoring is based on the knowledge of the applied treatments that are recorded at the two sites. Since 1994, samples of surface waters have been collected during each runoff event at the catchment outlet and on a vineyard plot, for which the applications of pesticides are precisely known. A network of perforated and buried bottles near the piezometers allows stratified sampling of groundwater at given depths, ranging from 0.5 to 5 m. The depth intervals between the bottles are ~1 m. Furthermore, soil samples are also collected for

chemical analysis on some vineyard plots. The number and type of molecules of pesticides and metabolites researched and analyzed have varied over time, depending on their use by farmers.

Erosion

Suspended sediment concentration is monitored for each runoff event using dedicated water samplers or the water samples collected for water chemistry. The water samples are first dried or filtered and then weighed to derive sediment concentrations in the runoff. In the downstream hydrometric station of each catchment, a continuous measurement of turbidity was added a few years ago to better capture the high-frequency dynamics of sediment fluxes. In Kamech, regular bathymetric surveys are performed to assess changes in the volume of sediment trapped in the outlet reservoir and to derive an erosion rate at the catchment scale (see Raclot and Albergel, 2006, for more explanation). All of these devices enable the evaluation of sediment fluxes and the establishment of a sediment budget at different timescales at the nested monitoring stations in the two catchments. Note that some analyses of pesticides, C and N nutrients, and metallic trace elements are also performed on the sediments (particulate phase) in a selection of runoff water samples.

Land Use, Agricultural Practices, and Soil Surface Characteristics

Because of their strong impact on runoff, erosion, and contamination by pesticides, a major effort is put into documenting land use, agricultural practices, and the resulting soil surface characteristics. Specific field surveys are dedicated to the monitoring of land use on all the plots of both catchments. Field surveys, conducted approximately once per month, permit the monitoring of visible agricultural practices, such as soil tillage, whereas farmer surveys allow for the documentation of other practices, mainly dates of application and types of pesticides used. Because of their strong effect on the infiltration rate and runoff generation, the soil surface characteristics are also observed during the field surveys, following the method proposed by Andrieux et al. (2001). Furthermore, other anthropogenic activities, such as water releases from the outlet reservoir in Kamech or maintenance of ditches in Roujan, are also recorded.

🔹 Dedicated Campaigns and Experiments

Numerous campaigns and short- and long-term experiments have been conducted within both catchments in relation to the scientific questions of the OMERE observatory, namely, the analysis of the high spatiotemporal variations of infiltration and runoff partitioning in relation to the spatial variations of soil properties and to the spatiotemporal variations of soil treatments. They mainly aimed (i) to determine permanent properties and (ii) to monitor, with high frequency and/or high spatial resolution, one or more variables of state or temporally variable properties. At

the beginning of the observatory, most surveys were conducted to understand the hydrological dynamics of the two catchments (e.g., infiltration of the soil surface in Leonard and Andrieux, 1998; aquifer systems and geochemistry in Bouzigues et al., 1997, and Tassinari et al., 2002; stream sources in Ribolzi et al., 2000; hydrological behavior in Moussa et al., 2002; and erosion flux in Albergel et al., 2003). As long-term hydrological monitoring equipment is described in the section above, we focus here on geophysical and remote sensing campaigns dedicated to soil properties or mapping of soil surface properties. In addition, a third part traces the evolution of the monitoring of ET flows, according to the development of new methodologies and new issues that we addressed.

Dedicated Geophysical Survey Campaigns for Soil Property Mapping

The use of indirect methods, such as geophysical surveys, to explore underground is necessary to avoid destructive and expensive drilling. Three types of techniques have been used in the observatory: (i) the self-potential signal to monitor groundwater levels and their variations, for which the observatory was a pilot site for methodological development (Revil et al., 2002; Suski et al., 2006; Linde et al., 2007); (ii) the electrical resistivity tomography (ERT); and (iii) the spectral analysis of surface waves (SASW). The last two techniques are used for bedrock mapping, which is a mandatory prerogative for each long-term observatory. In the lithologic and pedological context of the observatory, no conventional geophysical bedrock mapping method has been shown to be effective, due to the combination of uphill shallow and skeletal soils with downhill deep soils typical of Mediterranean head catchments and of a shallow water table. Spectral surface wave analysis and high-resolution classical ERT in wet and dry conditions were combined to map the bedrock depth of the Roujan catchment. The map was built from eight transects across the catchment and 81 drill holes, to calibrate geophysical measurements (Coulouma et al., 2012). The observatory databases were also used to compare three conventional geophysical approaches—dry ERT, diachronic ERT, and SASW—for mapping bedrock depth (Coulouma et al., 2013).

Dedicated Remote Sensing Campaigns for Soil Surface Property Mapping

Remote sensing surveys have been widely used in the observatory. The objective was to map permanent or variable soil properties involved in water, sediment, and contaminant transfers. The development of new methods and their applications constitute a major challenge, given the great spatial and temporal variability of soil properties and the variability of the transfers induced by agricultural activities and by the Mediterranean climate. On 2 Nov. 2010, a visible–near infrared (Vis-NIR, 0.4–2.5 μm) hyperspectral AisaDUAL image was acquired by plane across a study area (12 \times 25 km) including the Kamech catchment. As an emblematic example, the evaluation of the soil property prediction and spatialization based on Vis-NIR hyperspectral airborne data was performed (Gomez et al., 2012). The interest of combining a field

soil survey, airborne campaign, and simulated satellite data for the prediction of soil clay content at different spatial resolutions was also evaluated, providing maps of surface clay content from 5- to 30-m spatial resolution (Gomez et al., 2015).

With respect to time-varying properties, preliminary work has been conducted to map the soil surface characteristics, such as soil plant cover and soil crust (Wassenaar et al., 2005; Corbane et al., 2008a, 2008b, 2012). More recently, we have studied the ability of aerial photography with low-tech kites to obtain a decimeter digital elevation model. Aerial photography, with simple but appropriate equipment, has proven to be an alternative tool for surveying gullies with submetric details across the Kamech catchment (Feurer et al., 2018). Indeed, a decimetric-resolution digital elevation model of 3.18-km² area was constructed, with a mean error and a standard error in elevation of +7 and +22 cm, respectively.

Dedicated Campaigns for Evapotranspiration Fluxes: Technological Evolution

Several experimental campaigns have been devoted to the evaluation of the actual ET at various spatial scales, from field-scale to mesoscale catchments ($\sim 100 \text{ km}^2$). At the field scale, Trambouze et al. (1998) monitored different components of ET in a vineyard—soil evaporation and plant transpiration were measured using microlysimeters and sap-flows devices, respectively, and compared with Bowen-ratio ET measurements. Using eddy covariance measurements, Zitouna-Chebbi (2009) conducted several campaigns to characterize the evolution of ET for the main crops in the Kamech catchment. At the headwater catchment scale, Hébrard et al. (2006) analyzed spatial and temporal variability of surface soil moisture. Bsaibes (2007) and Zitouna-Chebbi (2009) used large aperture scintillometers to investigate flux tower eddy covariance measurements. At the mesoscale of the Peyne catchment (that includes the Roujan site), time series of thermal infrared images (taken with the Advanced Spaceborne Thermal Emission and Reflection Radiometer [ASTER] instrument aboard the Terra satellite) were used to evaluate remote sensing methods of ET retrieving across vineyards (Galleguillos et al., 2011a, 2011b).

🔹 Data Management and Policy

The long-term observations acquired in OMERE are all preprocessed and implemented in a dedicated PostgreSQL database called HYSAE, an acronym standing for HYdrologie Spatialisée-Agrosystème-Environnement (spatial hydrology-agrosystems-environment). The OMERE observatory has set up a quality assurance procedure based on the drafting of protocols that trace the data and their preprocessing from field acquisition to storage in the HYSAE database and backup on a remote datacenter. The applied preprocessing information is also stored in the database and can be retrieved with the dataset. The HYSAE database is coupled to a spatial data infrastructure, based on the GeOrchestra OpenSource solution, which mobilizes Geoserver for the management of Web Map/Web Feature Service flows and Geonetwork

for the metadata catalog. The OMERE spatial data infrastructure enables easy rendering and user-friendly cartographic querying of data, accessible via the internet (<http://www.obs-omere.org/>). Specific developments have also been made for the online visualization of time series. The observatory's long-term monitoring has been specially set up for and dedicated to online data access. Basic monitoring data are accessible without any embargo time, whereas additional data, including data acquired within a specific research project (e.g., a third-party-funded Ph.D. study), are accessible after a maximum embargo time of 5 yr. Some sensitive personal data (e.g., pesticides) or data acquired by third parties are not disseminated, in compliance with the information technology and freedom regulations that guarantee the confidentiality of personal data.

New Insights and Novel Scientific Findings

The OMERE observatory has led to many and various research results in the fields of hydrology, soil science, erosion, contaminant fate, agronomy and geography. Among these results, we focus hereafter on a few that we believe to be significant with respect to the three main objectives addressed by the observatory.

Water, Erosion, and Contaminant Fluxes: Estimation and Drivers

Several drivers of the mass fluxes in Mediterranean hilly areas have been identified from the OMERE observations. One main driver is the specific rainfall pattern in this region, with intense and uneven showers and long drought periods. The impact of rainfall pattern on hydrological cycles is well known and was confirmed by our observations, which emphasized that the Hortonian runoff mechanism is predominant in the OMERE catchments (Louchart et al., 2001; Moussa et al., 2002; Mekki et al., 2006; Raclot and Albergel, 2006). Accordingly, the main water, erosion and contaminant fluxes were observed to occur during intense rainfall events and were found to be very uneven (Louchart et al., 2001; Raclot et al., 2009; Smetanová et al., 2018). However, it must be noticed that during winter, despite the global water deficit at the annual scale, water tables can rise to the surface and create temporarily saturation excess runoff in small parts of the catchments. The impact of Mediterranean rainfall patterns on contaminant fate is less understood and was therefore studied in detail. We observed that pesticide losses occurred almost only during intense rainfall events by surface runoff and remained at a surprisingly high level several months after their application (Lennartz et al., 1997; Louchart et al., 2001, 2004). This latter observation could be explained as a consequence of drying periods that preserve a pesticide stock in the topsoil by slowing down its dissipation. This observation also allowed to notice from field observations and additional laboratory experiments that wetting/drying cycles lead to a systematic increase in sorption (Fig. 6). This result was much larger than previously measured in less variable

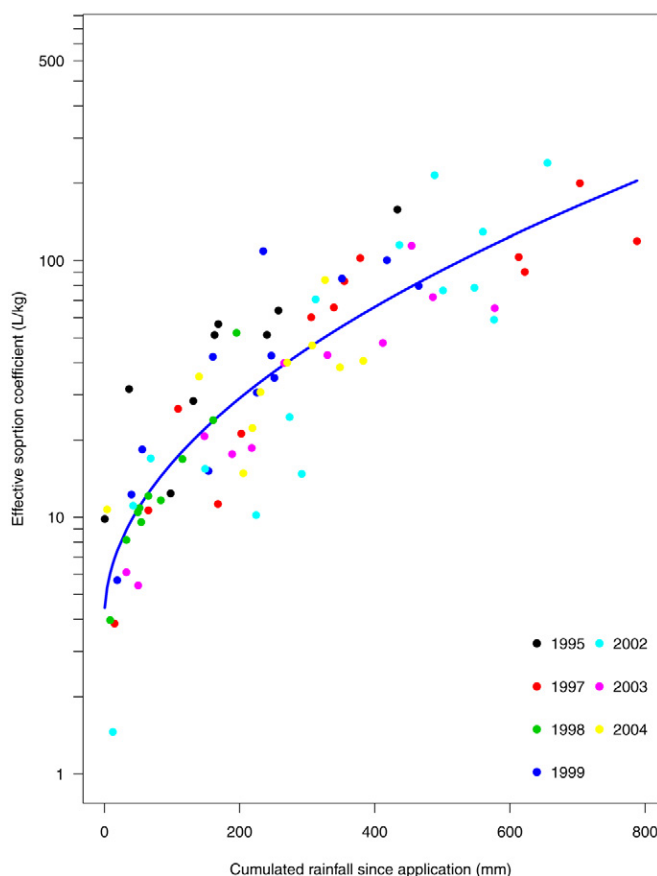


Fig. 6. Temporal variation in the effective sorption coefficient for diuron vs. cumulated rainfall since application, observed for 7 yr in Roujan (adapted from Louchart and Voltz, 2007).

environmental conditions (Louchart et al., 2005; Louchart and Voltz, 2007; Lennartz and Louchart, 2007; Saison et al., 2010).

Other main drivers of the observed water, erosion and contaminant fluxes were shown to be soil surface characteristics. Given the Hortonian runoff regime, these drivers strongly impact the soil infiltration-runoff partitioning (Leonard and Andrieux, 1998; Hébrard et al., 2006; Mekki et al., 2006), which influences all water and mass transport. The soil surface characteristics appeared to change largely with time, according to farming practices (e.g., soil tillage, chemical weed control or grass covering), soil type, erosion and swelling-shrinking processes (Leonard and Andrieux, 1998; Chahinian et al., 2006; Pare et al., 2011; Follain et al., 2012; Inoubli et al., 2016). The occurrence of soil cracks in the Kamech catchment controls local runoff generation and transfer within the fields (Inoubli et al., 2016). Their effect on water, erosion and contaminant fluxes proved to be of paramount importance (Lennartz et al., 1997; Louchart et al., 2001; Moussa et al., 2002; Raclot et al., 2009; Inoubli et al., 2016, 2017). Accordingly, soil tillage and soil surface management can be considered a powerful lever for controlling surface runoff and infiltration fluxes at the plot and catchment scales in the Mediterranean context.

A specific focus has also been given to the drivers of ET, which is the second major flux after rainfall in the Mediterranean

hydrological cycle. The relief and cropping patterns of the farmed land in the hilly areas of the OMERE catchments led us to examine the effects of slope and canopy geometry on the estimation and modeling of land ET. Indeed, concerning sloping conditions, a major knowledge gap is the influence of topography on the structure of turbulence within the boundary layer (Raupach and Finnigan, 1997). Few data exist in farmed hilly areas, although they are common in many parts of the world. In this respect, we collected eddy covariance measurements across a typical slope of the Kamech catchment and found that airflow inclination was strongly influenced by the combined effects of wind direction, topography, and vegetation height. Consequently, novel methods were developed to correct and gap-fill the eddy covariance measurements on slopes by considering vegetation height, slope, and wind direction at the field (Zitouna-Chebby et al., 2012, 2015; Boudhina et al., 2018) and hillslope scales (Zitouna-Chebby et al., 2018). As an example, Fig. 7 presents the seasonal evolution of actual ET across the northern hillslope of the Kamech catchment. The ratio of actual to reference ET was systematically high from fall to early spring and very low during summer; the interannual variability observed in spring and fall was related to the variability of rainfall amounts. Concerning crop geometry, the impact of row cropping on ET fluxes has already been demonstrated (Riou et al., 1994), but its simulation remained rather empirical. Dedicated monitoring campaigns (Trambouze et al., 1998; Trambouze and Voltz, 2001) enabled the acquisition of detailed ET and soil moisture data on rows and interrows at the vineyard scale to test and upgrade models for simulating ET of crops planted in rows. The main improvements were the inclusion of a dedicated light interception scheme in existing models (Bsaibes, 2007; Galleguillos et al., 2017) and the development of a three-source Soil–Vegetation–Atmosphere Transfer (SVAT) model, dedicated to grassed vineyards (Montes et al., 2014).

Aggregation Effects of Farming and Land Management

A major issue when studying farmed catchments is to understand how farming and land management at the local scale influence water and soil resources at the catchment scale. Analysis of the observed data at plot, hillslope, and catchment scales has allowed for the identification of several specific situations, according to the nature of fluxes and land management. In this respect, the comparison of Roujan and Kamech catchments was fruitful since they exhibit different features of land management. Indeed, both catchments exhibit farming across a large part of their area, but in Roujan, land management over the centuries has led to terraced slopes and a man-made hydrographic network, whereas in Kamech, land management has only consisted of the building of a hill reservoir at the catchment outlet, and the natural hydrographic network that consists of a dense network of long-term stable gullies has not been deeply modified (i.e., perennial).

The scale effect, namely, the issues related to the extrapolation (upscaling) of local (field) measurements or fluxes to catchments,

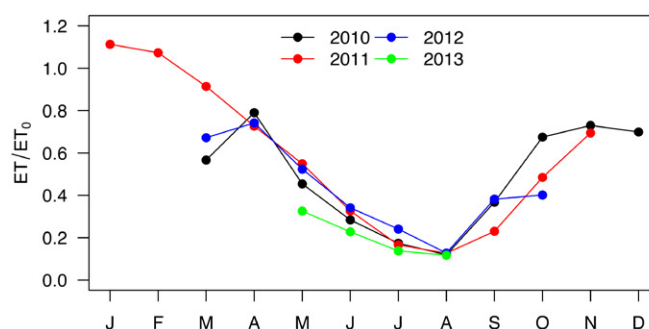


Fig. 7. Seasonal evolution of the ratio of actual (ET) to reference (ET_0) evapotranspiration at the hillslope scale across 4 yr in Kamech. Actual evapotranspiration was measured by the flux tower installed on the northern hillslope of Kamech, whereas ET_0 was measured by the meteorological station (adapted from Zitouna-Chebby et al., 2018).

was studied for surface runoff and erosion transfers in both catchments. Large-scale effects were observed in the Roujan catchment as a result of its network of ditches that collect water and erosion fluxes from the fields and route them to the outlet. Observations confirmed their overall control on floods (Moussa et al., 2002), groundwater recharge (Dagès et al., 2009), erosion fluxes (Raclot et al., 2009), or pesticide transfer (Louchart et al., 2001; Dagès et al., 2015; Dollinger et al., 2016, 2017, 2018). The estimation of the hydrological water balance of the central depression of the Roujan catchment (Fig. 8) showed that, despite comprising a small fraction of the area (1% of catchment area), ditches concentrate 50% of autumnal groundwater recharge (Dagès et al., 2009), which indicates the existence of substantial reinfiltration in ditches. It thus explains, in part, that the observed annual erosion rate and herbicide losses at the catchment outlet are more than one order of magnitude less than the sum of the edge of field losses (Louchart et al., 2001; Raclot et al., 2009; Dagès et al., 2015; Dollinger et al., 2018). For erosion, the scale effect must also be related to sedimentation in the interfield elements (e.g., in natural vegetation strips at the edges of the plots or in ditches). For pesticides, significant retention processes occur during transport in ditches because of sorption to the ditch bed soil material, whose characteristics vary largely, according to the maintenance operations of the ditch (Dollinger et al., 2016, 2017). Conversely, the presence of a dense ditch network in the Roujan catchment was observed to weaken the general hillslope effect on the spatial variation of soil water content, which is observed in many catchments where the influence of topography leads to much wetter downslope areas than those upslope. Indeed, the ditch network suppresses or restricts the lateral connectivity between fields with regard to surface runoff. Hébrard et al. (2006) thus observed that spatial variation of top-soil water content was predominantly controlled by the field soil surface characteristics, as related to farming practices, and not by nonlocal factors such as topography attributes. In the same line, it was found that ET fluxes across the catchment could be evaluated by simply aggregating the field-scale fluxes (Bsaibes, 2007). This result justified the estimation of vineyard ET across large areas,

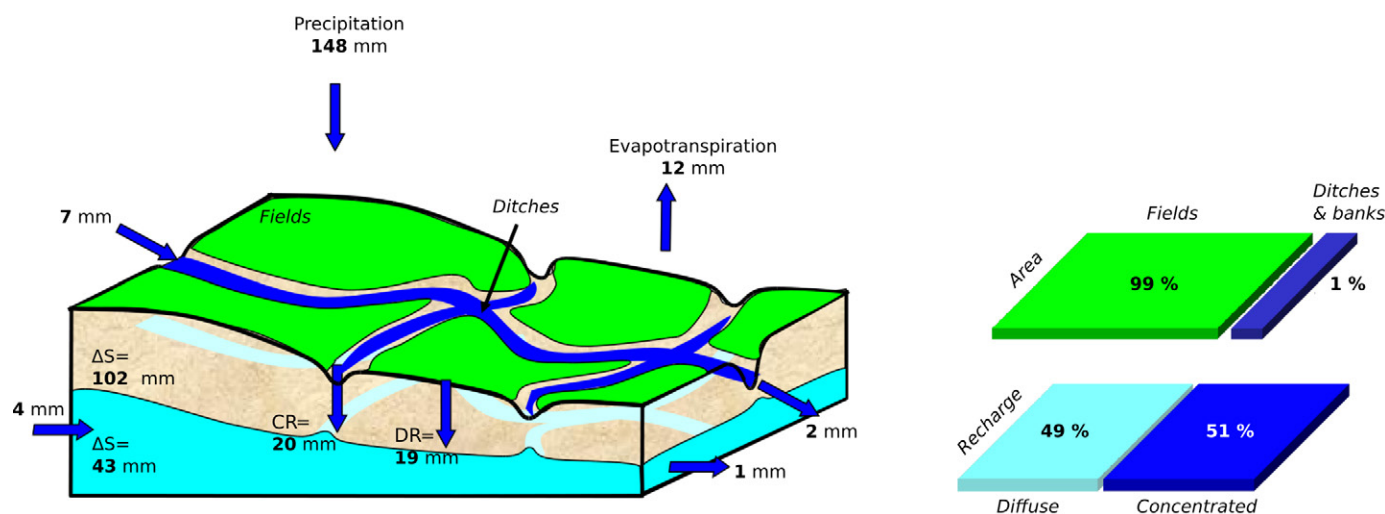


Fig. 8. Water balance of the central depression of the Roujan catchment, calculated for the period of 7 to 20 Oct. 2005. CR, DR, and ΔS stand for concentrated recharge, diffuse recharge, and water volume variations in groundwater and in the vadose zone, respectively (adapted from Dagès et al., 2009).

using remote sensing methods, by combining field-scale ET estimation derived from soil moisture content and eddy covariance flux tower (Galleguillos et al., 2011a, 2011b, 2017).

In the Kamech catchment, in contrast with Roujan, runoff and erosion rates and their dynamics were found to be of the same order of magnitude at field and catchment outlets (Mekki et al., 2006; Inoubli et al., 2017), suggesting a small influence of the gullies network. Two specific surveys were thus conducted to better understand the role of gullies in Kamech: one at the gully scale using regular intensive field surveys (El Khalili et al., 2013), and a second at catchment-scale using a radionuclide-based fingerprinting approach (Ben Slimane et al., 2013). The results showed that rill and interrill erosion contributed $\sim 80\%$ of the outlet sediment fluxes, which means that gullies in Kamech behave more as elements facilitating water and sediment transfer than as sediment sources or sediment trapping locations, which is very different from the ditch networks in Roujan. However, applications of fingerprinting methods in four other Tunisian reservoirs showed that the role of gully erosion in total erosion is very dependent on the catchment context (Ben Slimane et al., 2016). Concerning a hill reservoir, which is typical of the water-harvesting structures that have been increasingly adopted in Mediterranean regions, the observations of OMERE were aimed at establishing its water balance. The impact of hill reservoirs on the depletion of hydrological regimes downstream is well known, but their impact on the whole hydrological balance had not been quantified in the literature. A thorough water balance analysis in Kamech demonstrated that the reservoir–subsurface exchanges were by far the main output component in water balance (Bouteffeha et al., 2015). This result may somewhat change the paradigm of hill reservoir water management, as it generally relies on a tradeoff between keeping water in the reservoir for the long-term use in the dry season and using water in the short term to avoid losses by evaporation. Knowledge that the major losses are probably due to infiltration

to groundwater suggests that the key water harvesting effect of hill reservoirs may rather be to recharge groundwater and strengthen deep water resources.

In summary, the OMERE observations clearly illustrate the major impact of land management on hydrological variables in the Mediterranean context. According to the state or flux variables, land management can either reinforce or blur the difference in hydrological response between field and catchment but is always a main factor to be taken into account for understanding, predicting, and managing water resources in Mediterranean catchments.

Toward New Scenarios for Sustainable Agricultural Management

The design and evaluation of scenarios for more sustainable agricultural management and improved ecosystem services in farmed Mediterranean landscapes have been one of the main long-term objectives of the observatory. Because experiments at the catchment scale are not feasible, modeling approaches were adopted to answer the latter objective and to allow for the numerical evaluation of scenarios. To this aim, in a first step, a series of physically based hydrological models have been progressively developed, taking into account the main processes and drivers of water, erosion, and contaminant fluxes in both OMERE catchments. The main specific and common feature of the developed models is the subdivision of each catchment into “hydrological units” of irregular shape, according to the hydrological discontinuities of farmed catchments. This feature allows the explicit representation of many of the particular characteristics of farmed areas, such as field boundaries, change in land use, and agricultural practices between fields, grass strips, ditches, and bank networks. The series of models consists of MHYDAS (Moussa et al., 2002) for runoff generation and transfer, MHYDAS-Erosion (Gumiere et al., 2011), and LandSoil (Ciampalini et al., 2012) for soil erosion and particle transfer, MHYDAS-Pesticides

(Bouvet et al., 2010) for organic contaminant transfer, and GeoMHYDAS for landscape segmentation (Lagacherie et al., 2010), with MHYDAS standing for Modélisation hydrologique spatialisée des agrosystèmes (spatially distributed hydrological modeling of agrosystems). The OMERE database has been extensively used for calibrating and validating the models. Multiscale calibration procedures were specifically developed for taking advantage of the OMERE nested monitoring system (Hallema et al., 2013, Gumiere et al., 2014). Moreover, to support the development of these models, a comprehensive software platform, OpenFLUID, was set up for helping modelers to build spatially distributed landscape models (Fabre et al., 2010).

Several applications of these models have already been used. Most of them first intended to analyze the impact of landscape organization, namely, the distribution of agricultural field management and land infrastructures, on soil and water resources. Second, the applications were intended to derive the optimal design of land management for improving ecosystem services. The earliest applications studied numerically whether catchment streamflow and erosion can vary significantly, depending on ditch network geometry and topology (Moussa et al., 2002;

Levavasseur et al., 2012), and on the spatial organization of soil tillage, weeding practices, or vegetated filter strips (e.g., Fig. 9; Moussa et al., 2002; Biarnès and Colin, 2006; Colin et al., 2012; Gumiere et al., 2015). These applications also determined the optimal spatial organization of the latter management practices that maximizes or minimizes runoff characteristics (peak, time lag, volume, etc.). Additionally, scenarios of global change, combining climate change and land-use change, were tested for guiding soil conservation practices (David et al., 2014; Paroissien et al., 2015). Other applications concerned the assessment of the influence of landscape spatial organization on pesticide dissipation. In a multidisciplinary study, MHYDAS pesticide was used for evaluating several soil treatment strategies in Mediterranean vineyard areas, chosen by a group of experts to restrict the use of herbicides and decrease the overall water contamination by pesticides but still secure grape yields (Biarnès et al., 2017). In another study, the influence of the geometry of ditches and of their spatial distribution on pesticide fate within the catchment was also addressed by simulation. The results obtained to date indicate the possibility for increasing pesticide retention of the ditch networks by adapting their geometry and by specific

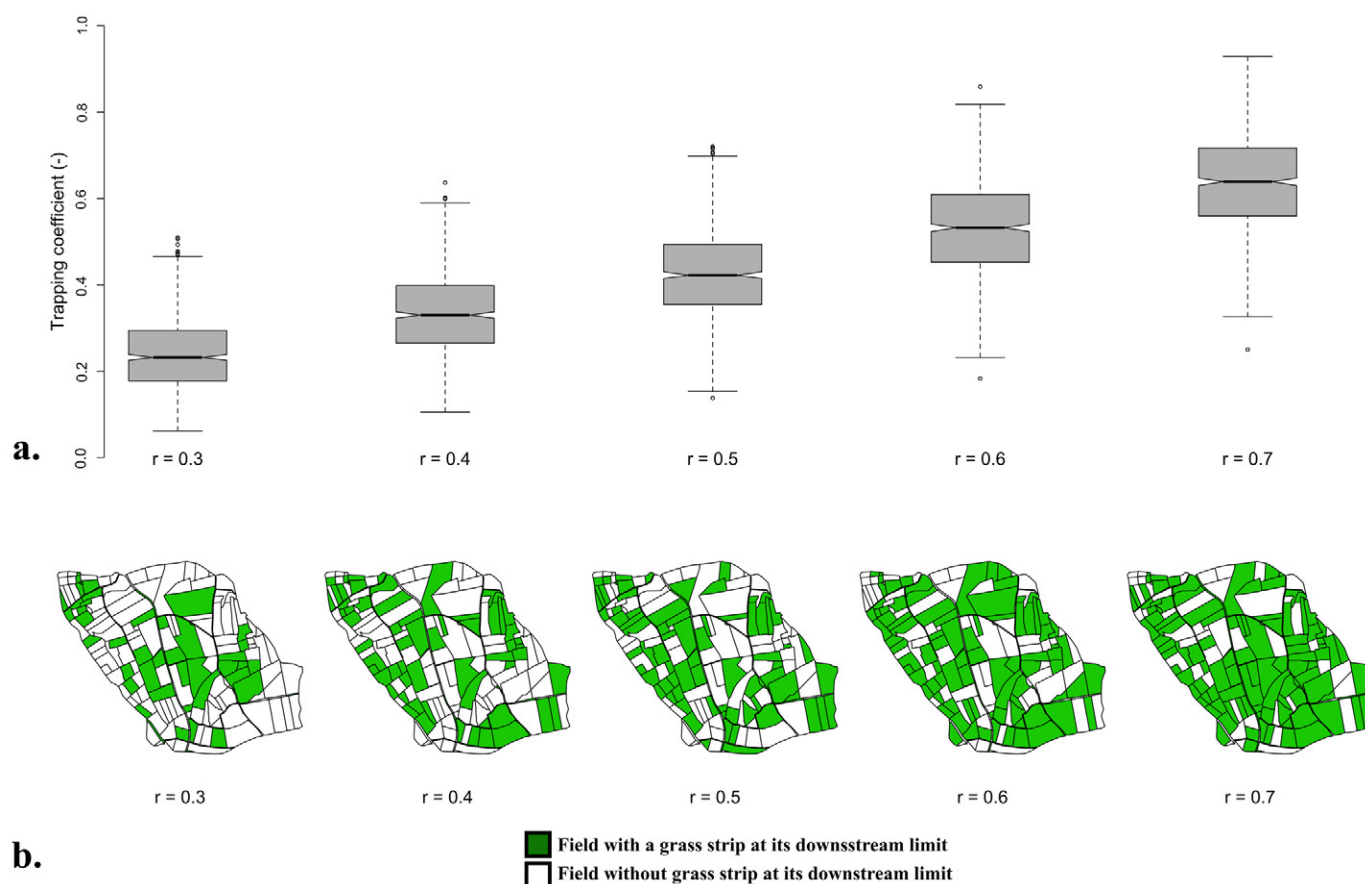


Fig. 9. Simulated effects of grass strip density on the sediment yield at the Roujan catchment outlet, using the MHYDAS-Erosion model and a stochastic generation model of grass strip locations. Panel (a) shows boxplots of the sediment trapping efficiency (i.e., the percentage of sediment reduction due to sediment trapping by grass strips, considering a grass strip density $[r]$ varying from 0.3 to 0.7 and 800 repetitions of grass strip locations computed according to a Monte Carlo-based numerical procedure). The notches indicate the 95% confidence interval of the median value, and the whiskers indicate the 25th and 75th percentiles of the trapping coefficient distribution. Panel (b) shows the best configuration of grass strip locations, with regard to soil loss reduction at the Roujan outlet, for grass strip density ranging from 0.3 to 0.7 (adapted from Gumiere et al., 2015).

maintenance operations (Dagès et al., 2016). All these simulation results helped to produce guidelines for improved soil and water management by local stakeholders.

Retrospective Analysis of Observation Design Evolution

The OMERE observatory was founded in 2002, but the two farmed catchments had already been in operation since the 1990s. Therefore, the observation design of OMERE is now more than 25 yr old. It largely evolved during this period. Below, we share some lessons that emerge, in our opinion, from the long-term monitoring experience and conclude with some perspectives.

First, the instrumentation design has to be permanently improved and questioned. This design is related not only to the evolution of measurement techniques, but also and even more to the natural change and expansion of scientific issues that the observatory aims to meet. As previously mentioned, the OMERE catchments were first established to elucidate the influence of changes in land-use practice on surface water resources. Regarding land-use practices, both catchments were particularly relevant for studying farming practices and landscape infrastructures, such as ditches in Roujan and hill reservoirs in Kamech. Accordingly, from the beginning, a monitoring design with embedded spatial scales from plot to catchment scales was defined. However, it was mainly limited to monitoring surface runoff. With time, it became clear that land-use practices had a very strong influence on many interacting fluxes, and reciprocally, that they were also affected by these fluxes at the landscape scale. Therefore, a more comprehensive observation design was developed, step by step, for monitoring all components of the hydrological balance, namely, surface–subsurface interactions and atmospheric fluxes. The design also considered the monitoring of sediment fluxes, since farmers and local land managers expressed their interest in this topic. In contrast, the monitoring of contaminant fluxes was due to the initiative of a researcher and took place after a few years. This monitoring has yet to be reinforced on the Kamech observatory. However, at the start of the OMERE observatory in the early 1990s, it was already well observed that intensive agriculture was a source of water pollution by nitrates and pesticides in North America and northern Europe, but little information was available in Mediterranean regions, and most farmers and land managers were not aware of this threat or preferred to ignore it. Given the intense use of pesticides on permanent Mediterranean crops such as vineyards or fruit orchards, on one hand, and the intense wash-off potential of the Mediterranean rain events, on the other hand, it was very probable that Mediterranean agricultural areas had to face water pollution issues, similar to those of more northerly regions but with different patterns. The data collected in the Roujan catchment helped to recognize the issue and to guide the farmers in modifying their weeding practices. This illustrated the potential role of an environmental long-term observatory in anticipating new environmental and social issues.

Second, long-term monitoring is not self-evident at first sight, neither for those who manage observatories, nor for funding agencies or for the scientific community. This became evident only with time. When the OMERE catchments were initiated, they were thought to last only a few years, until a good picture of the impacts of land-use changes on hydrological flows could be obtained. Progressively, several reasons motivated researchers to maintain and to expand the observation facility for longer terms. The first reason was the inherent temporal variability of processes that required long-term observation to identify either slow-rate processes or scarce events with strong impacts. This point is illustrated by the pesticide losses, occurring mainly during a few intense rainfall events by surface runoff, while desorption rates are submitted to slow changes at the seasonal timescale (Lennartz et al., 1997; Louchart et al., 2001, 2004). A second reason was the advantage of using the observatory for short-term specific experimental investigations. On this point, the established basic observation infrastructure and the available monitoring records of the observatory facilitate both the implementation of any new investigation and the discussion of the generic significance of its results, within the variability of processes already observed. A third reason was the attractiveness of a unique experimental site to foster multidisciplinary collaborative work and the establishment of common research paradigms between scientific fields. For example, collaborative actions involving hydrology and geophysics allowed the development and testing of the self-potential method to monitor infiltration rates and groundwater levels (Revil et al., 2002; Suski et al., 2006; Linde et al., 2007).

Third, in environmental sciences, observation infrastructures have to be linked as closely as possible to modeling approaches. Modeling helps to interpret the observed dynamics and to test hypotheses about the underlying mechanism and can also guide the design of the observation setup. Moreover, modeling is a means for extending the significance of the results of an observatory. Indeed, the general significance of the observations provided by environmental observatories such as OMERE is intrinsically limited by the specific characteristics of the instrumented area and by those of the observational periods. In this respect, fitting and testing models with an extensive database helps not only to improve models but also to extract general information from the database, such as the values of physically based model parameters. This will then support simulation in different locations and/or time periods, provided that the acting processes remain similar. As an example, due to the OMERE database, the MHYDAS-Pesticides model was thoroughly fitted and could be applied successfully on other vineyard catchments to compare the impact of soil treatment scenarios (Biarnès et al., 2017). Similarly, the adaptation of the Hydrus-1D model to row vineyards (two-dimensional) was first tested using the OMERE database before being applied to vineyards located in the surrounding region (Galleguillos et al., 2017).

Conclusions and Perspectives

Here, we have provided an overview of the OMERE observatory, a Mediterranean observatory that contains two farmed

catchments in Tunisia and France. The OMERE observatory aims at documenting the impact of agricultural and land management on mass fluxes in farmed catchments of the Mediterranean region. In accordance with its initial specific objectives, over the last 25 yr, the observatory has allowed us to obtain new insights into elementary processes (e.g., ET, runoff generation, contaminant fate) and to better understand the impacts of anthropogenic activities (farming practices and landscape features such as ditch, small reservoir, or field margins) on water, contaminant, and sediment transfer in water, as well in soil of farmed Mediterranean catchments. The observatory has also conducted research on the understanding of the effect of local farming and land management on water and soil resources at the catchment scale. Physically based hydrological models were developed and tested, based on the understanding and data from the observatory. The models helped to analyze the impact of landscape organization on soil and water resources. Much of the research conducted using the observatory has led to multi- and interdisciplinary collaborations involving hydrology, geochemistry, agronomy, geography, and sociology. Below, we attempt to present our major future plans for OMERE from both the instrumental and thematic points of view.

Seeking higher spatial and temporal resolution of the measurement design is clearly one of our major aims for the future. For several variables, given their intrinsic variability, the present measurement resolution is not satisfactory. For example, this is the case for the monitoring of the contamination pattern of shallow water tables. The spatial density of piezometers has to be increased strongly to capture the overall related contamination variations that are largely influenced by concentrated recharge from the ditch networks. The spatial resolution of soil moisture content could also be refined using new technical developments, based on multi-temporal radar satellite imagery (Tomer et al., 2015). Better spatial and temporal characterization of landscape and soil properties will also benefit from low-altitude imagery (Feurer et al., 2018).

Moving progressively from an agro-hydrological observatory to an agroecological observatory is another prospect. Until now, OMERE has focused mainly on the study of the impact of agricultural land management on soil and water resources. The results obtained to date clearly show that agricultural practices indeed have a paramount influence on the fate of ecosystem resources in Mediterranean areas. A new and additional challenge is to use the OMERE observatory for designing sustainable agricultural management practices. To answer this challenge, we believe that OMERE should follow a more comprehensive observation strategy, in line with agroecological approaches that consider the interactions between plants, animals, humans, and the environment in a systemic way (Wezel et al., 2009). Accordingly, there are three main developments we are seeking. One development is to build a more complete view of the contamination pathways of the ecosystem compartments, especially by investigating pathways at the air–soil–water interfaces and at the surface–subsurface interface. Another development is to include the field margins and the non-cultivated landscape elements in the observation network to better

understand the impact of spontaneous vegetation areas on water, sediment, and contaminant transfer and, reciprocally, the impact of these latter fluxes on biodiversity. A third development is to go beyond the mere observation of agricultural practices and to analyze the farmers' management strategies that are behind these practices to study their flexibility toward new practices. The efficacy of these developments will require opening OMERE observatory to a larger range of scientific fields, including atmospheric, ecological, and social sciences.

Acknowledgments

The OMERE observatory is supported by the Institut National de la Recherche Agronomique (INRA, France), the Institut de Recherche pour le Développement (IRD, France), the Institut National du Génie Rural, des Eaux et des Forêts (INRGREF, Tunisia), the Institut National Agronomique de Tunisie (INAT, Tunisia), and the Centre National de la Recherche Scientifique (CNRS, France). We thank the past and present directors of these organizations and institutions. The OMERE observatory belongs to the French network of critical zone observatories OZCAR-RI, which is supported by the French Ministry of Education and Research, through the Allenvi Alliance; it was also supported by the Equipex CRITEX. We would like to acknowledge the present and past contract employees, masters and Ph.D. students, and their supervisors. All concerned people could not be cited in the article. We thank all the farmers and village inhabitants of the two catchments areas for the comprehension and the interest they have in the OMERE's activities. We thank the two anonymous reviewers and Heye Bogen, Associate Editor, for helpful comments and suggestions to improve the manuscript, as well as Olivier Bour, *Vadose Zone Journal* Associate Editor, for encouraging us to submit the manuscript to this special section.

References

- Albergel, J., P. Yannick, S. Nasri, and M. Boufaroua. 2003. Erosion et transport solide dans des petits bassins versants méditerranéens. In: E. Servat, et al., editors, *Hydrology of the Mediterranean and semiarid regions. Proceedings of an international symposium held at Montpellier, France. 1–4 Apr. 2003*. Publ. 278. Int. Assoc. Hydrol. Sci., Wallingford, UK. p. 373–379.
- Andrieux, P., A. Hatier, J. Asseline, G. de Noni, and M. Voltz. 2001. Predicting infiltration rates by classifying soil surface features in a Mediterranean wine-growing area. Paper presented at "The significance of soil surface characteristics in soil erosion." COST 623. "Soil Erosion and Global Change" international symposium, Strasbourg, France. 20–22 Sept. 2001. INRA, Paris.
- Ben Slimane, A., D. Raclot, O. Evrard, M. Sanaa, I. Lefèvre, M. Ahmadi, et al. 2013. Fingerprinting sediment sources in hillside reservoir within a cultivated catchment of Tunisia. *J. Soils Sediments* 13:801–815. doi:10.1007/s11368-012-0642-6
- Ben Slimane, A., D. Raclot, O. Evrard, M. Sanaa, I. Lefèvre, and Y. Le Bissonnais. 2016. Relative contribution of rill/interrill and gully/channel erosion to small reservoir siltation in Mediterranean environments. *Land Degrad. Dev.* 27:785–797. doi:10.1002/ldr.2387
- Biarnès, A., P. Andrieux, J.M. Barbier, A. Bonnefoy, C. Compagnone, X. Delpuech, et al. 2017. Evaluer par modélisation des stratégies de réduction des usages d'herbicides dans les bassins versants viticoles. *Innovations Agron.* 57:141–152.
- Biarnès, A., and F. Colin. 2006. Methodology for assessing the hydrological impact of weed control practices with a view to management of Mediterranean vinegrowing catchments. *Int. J. Sustain. Dev.* 9:9161–9179. doi:10.1504/IJSD.2006.011639
- Bogen, H.R., M. Herbst, J.A. Huisman, U. Rosenbaum, A. Weuthen, and H. Vereecken. 2010. Potential of wireless sensor networks for measuring soil water content variability. *Vadose Zone J.* 9:1002–1013. doi:10.2136/vzj2009.0173
- Boudhina, N., R. Zitouna-Chebbi, I. Mekki, F. Jacob, N. Ben Mechlia, M. Masmoudi, and L. Prévot. 2018. Evaluating four gap-filling methods for eddy covariance measurements of evapotranspiration over hilly crop fields. *Geosci. Instrum., Methods Data Syst.* 7:151–167. doi:10.5194/gi-7-151-2018

- Bouteffeha, M., C. Dages, R. Bouhlila, and J. Molenat. 2015. A water balance approach for quantifying subsurface exchange fluxes and associated errors in hill reservoirs in semiarid regions. *Hydrol. Processes* 29:1861–1872. doi:10.1002/hyp.10308
- Bouvet, L., X. Louchart, M. Barès, S. Lalauze, R. Moussa, and M. Voltz. 2010. Modélisation intégrée des agro-hydrosystèmes avec MHYDAS: Exemple des transferts de pesticides en milieu viticole méditerranéen. In: J.F. Cooper, et al., editors, *Proceedings of the 40th Colloquium of the GFP*, Banyuls-sur-Mer, France. 26–28 May 2010. Ecole des Mines, Paris.
- Bouzigues, R., O. Ribolzi, J.C. Favrot, and V. Valles. 1997. Carbonate redistribution and hydrogeochemical processes in two calcareous soils with groundwater in a Mediterranean environment. *Eur. J. Soil Sci.* 48:201–211. doi:10.1111/j.1365-2389.1997.tb00541.x
- Bsaibes, A. 2007. Evaluation d'une approche multi-locale d'estimation spatiale de l'évapotranspiration sur un bassin versant agricole hétérogène en région méditerranéenne, Ph.D. diss., Univ. Montpellier, Montpellier, France.
- Chahinian, N., M. Voltz, R. Moussa, and G. Trotoux. 2006. Assessing the impact of the hydraulic properties of a crusted soil on overland flow modelling at the field scale. *Hydrol. Processes* 20:1701–1722. doi:10.1002/hyp.5948
- Ciampalini, R., S. Follain, and Y. Le Bissonnais. 2012. LandSoil: A model for analysing the impact of erosion on agricultural landscape evolution. *Geomorphology* 175–176:25–37. doi:10.1016/j.geomorph.2012.06.014
- Colin, F., R. Moussa, and X. Louchart. 2012. Impact of the spatial arrangement of land management practices on surface runoff for small catchments. *Hydrol. Processes* 26:255–271. doi:10.1002/hyp.8199
- Corbane, C., P. Andrieux, M. Voltz, J. Chadoeuf, J. Albergel, J.M. Robbez-Masson, and P. Zante. 2008a. Assessing the variability of soil surface characteristics in row-cropped fields: The case of Mediterranean vineyards in southern France. *Catena* 72:79–90. doi:10.1016/j.catena.2007.04.006
- Corbane, C., F. Jacob, D. Raclot, J. Albergel, and P. Andrieux. 2012. Multitemporal analysis of hydrological soil surface characteristics using aerial photos: A case study on a Mediterranean vineyard. *Int. J. Appl. Earth Obs. Geoinf.* 18:356–367. doi:10.1016/j.jag.2012.03.009
- Corbane, C., D. Raclot, F. Jacob, J. Albergel, and P. Andrieux. 2008b. Remotely sensed soil surface characteristics with a multiscale object oriented approach. *Catena* 75:308–318. doi:10.1016/j.catena.2008.07.009
- Coulouma, G., P. Lagacherie, K. Samyn, and G. Grandjean. 2013. Comparisons of dry ERT, diachronic ERT and the spectral analysis of surface waves for estimating bedrock depth in various Mediterranean landscapes. *Geoderma* 199:128–134. doi:10.1016/j.geoderma.2012.07.026
- Coulouma, G., K. Samyn, G. Grandjean, S. Follain, and P. Lagacherie. 2012. Combining seismic and electric methods for predicting bedrock depth along a Mediterranean soil toposéquence. *Geoderma* 170:39–47. doi:10.1016/j.geoderma.2011.11.015
- Dagès, C., J.S. Bailly, J. Dollinger, P. Lagacherie, and M. Voltz. 2016. Guide méthodologique: Diagnostic et gestion des réseaux de fossés agricoles infiltrants pour la limitation de la contamination des masses d'eau par les pesticides. INRA, UMR, LISAH, Montpellier, France. doi:10.13140/RG.2.2.30264.60168
- Dagès, C.M.V., A. Bsaibes, L. Prévot, O. Huttel, X. Louchart, and S. Negro. 2009. Estimating the role of a ditch network in groundwater recharge in a Mediterranean catchment using a water balance approach. *J. Hydrol.* 375:498–512. doi:10.1016/j.jhydrol.2009.07.002
- Dagès, C., A. Samouélian, S. Negro, V. Storck, O. Huttel, and M. Voltz. 2015. Seepage patterns of diuron in a ditch bed during a sequence of flood events. *Sci. Total Environ.* 537:120–128. doi:10.1016/j.scitotenv.2015.07.130
- David, M., S. Follain, R. Ciampalini, Y. Le Bissonnais, A. Couturier, and C. Walter. 2014. Simulation of medium-term soil redistributions for different land use and landscape design scenarios within a vineyard landscape in Mediterranean France. *Geomorphology* 214:10–21. doi:10.1016/j.geomorph.2014.03.016
- de Franchis, L., and L. Ibanez. 2003. Threats to soils in Mediterranean countries: Document review. Plan Bleu Paper 2. United Nations Environ. Progr., Sophia Antipolis, France. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.460.6771&rep=rep1&type=pdf> (accessed 28 Sept. 2018).
- Dollinger, J., C. Dages, S. Negro, J.S. Bailly, and M. Voltz. 2016. Variability of glyphosate and diuron sorption capacities of ditch beds determined using new indicator-based methods. *Sci. Total Environ.* 573:716–726. doi:10.1016/j.scitotenv.2016.08.168
- Dollinger, J., C. Dagès, A. Samouelian, G. Coulouma, M. Lanoix, Y. Blanca, and M. Voltz. 2018. Contrasting soil property patterns between ditch bed and neighbouring field profiles evidence the need of specific approaches when assessing water and pesticide fate in farmed landscapes. *Geoderma* 309:50–59. doi:10.1016/j.geoderma.2017.09.006
- Dollinger, J., F. Vinatier, M. Voltz, C. Dagès, and J.S. Bailly. 2017. Impact of maintenance operations on the seasonal evolution of ditch properties and functions. *Agric. Water Manage.* 193:191–204. doi:10.1016/j.agwat.2017.08.013
- El Khalili, A., D. Raclot, H. Habaieb, and J.M. Lamachère. 2013. Factors and processes of permanent gully evolution in a Mediterranean marly context (Cape Bon, Tunisia). *Hydrol. Sci. J.* 58:1519–1531. doi:10.1080/02626667.2013.824086
- European Soil Data Centre. 2014. The soil map of Europe. *Eur. Comm. Joint Res. Ctr. Inst. Environ. Sustainability*. <http://eusoils.jrc.ec.europa.eu/>
- Fabre, J.C., X. Louchart, F. Colin, C. Dagès, R. Moussa, M. Rabotin, et al. 2010. OpenFLUID: A software environment for modelling fluxes in landscapes. In: *Proceedings of LANDMOD2010 International Conference on Integrative Landscape Modelling*, Montpellier, France. 3–5 Feb. 2010. UMR LISAH, Montpellier. <https://www.umr-lisah.fr/rtra-projects/LANDMOD2010-proceedings/docs/ART-00002400.pdf> (accessed 28 Sept. 2018)
- Feurer, D., O. Planchon, M.A. El Maaoui, A. Ben Slimane, M.R. Boussema, M. Pierrot-Deseilligny, and D. Raclot. 2018. Using kites for 3-D mapping of gullies at decimeter resolution over several square kilometers: A case study on the Kamech catchment, Tunisia. *Nat. Hazards Earth Syst. Sci.* 18:1567–1582. doi:10.5194/nhess-18-1567-2018
- Follain, S., R. Ciampalini, A. Crabit, G. Coulouma, and F. Garnier. 2012. Effects of redistribution process on rock fragment variability within a vineyard topsoil in Mediterranean France. *Geomorphology* 175–176:45–53. doi:10.1016/j.geomorph.2012.06.017
- Gaillardet, J., I. Braud, F. Hankard, O. Bour, S. Anquetin, N. Dorfliger, et al. 2018. OZCAR: The French network of critical zone observatories. *Vadose Zone J.* 17:180067. doi:10.2136/vzj2018.04.0067
- Galleguillos, M., F. Jacob, L. Prévot, C. Faunndez, and A. Bsaibes. 2017. Estimation of actual evapotranspiration over a rainfed vineyard using a 1-D water transfer model: A case study within a Mediterranean watershed. *Agric. Water Manage.* 184:67–76. doi:10.1016/j.agwat.2017.01.006
- Galleguillos, M., F. Jacob, L. Prévot, A. French, and P. Lagacherie. 2011a. Comparison of two temperature differencing methods to estimate daily evapotranspiration over a Mediterranean vineyard watershed from ASTER data. *Remote Sens. Environ.* 115:1326–1340. doi:10.1016/j.rse.2011.01.013
- Galleguillos, M., F. Jacob, L. Prévot, P. Lagacherie, and S. Liang. 2011b. Mapping daily evapotranspiration over a Mediterranean vineyard watershed. *IEEE Geosci. Remote Sens. Lett.* 8:168–172. doi:10.1109/LGRS.2010.2055230
- García-Ruiz, J.M., E. Nadal-Romero, N. Lana-Renault, and S. Beguería. 2013. Erosion in Mediterranean landscapes: Changes and future challenges. *Geomorphology* 198:20–36. doi:10.1016/j.geomorph.2013.05.023
- Gomez, C., P. Lagacherie, and G. Coulouma. 2012. Regional predictions of eight common soil properties and their spatial structures from hyperspectral Vis–NIR data. *Geoderma* 189–190:176–185. doi:10.1016/j.geoderma.2012.05.023
- Gomez, C., R. Oltra Carrio, P. Lagacherie, S. Bacha, and X. Briottet. 2015. Sensitivity of soil property prediction obtained from Hyperspectral Vis–NIR imagery to atmospheric effects and degradation in image spatial resolutions. *Remote Sens. Environ.* 164:1–15. doi:10.1016/j.rse.2015.02.019

- Gumiere, S., J.S. Bailly, B. Cheviron, D. Raclot, Y. Le Bissonnais, and A. Rousseau. 2015. Evaluating the impact of the spatial distribution of land management practices on water erosion: Case study of a Mediterranean catchment. *J. Hydrol. Eng.* 20:C5014004. doi:10.1061/(ASCE)HE.1943-5584.0001076
- Gumiere, S., M. Delattre, Y. Le Bissonnais, B. Cheviron, A. Ben Slimane, and D. Raclot. 2014. Multi-scale calibration and validation of MHYDAS-Erosion for a small Mediterranean vineyard catchment: A case study. *Rev. Sci. Eau* 27:21–36. doi:10.7202/1021980ar
- Gumiere, S.J., D. Raclot, B. Cheviron, G. Davy, X. Louchart, J.-C. Fabre, et al. 2011. MHYDAS-Erosion: A distributed single-storm water erosion model for agricultural catchments. *Hydrol. Processes* 25:1717–1728. doi:10.1002/hyp.7931
- Hallema, D.W., R. Moussa, P. Andrieux, and M. Voltz. 2013. Parameterization and multi-criteria calibration of a distributed storm flow model applied to a Mediterranean agricultural catchment. *Hydrol. Processes* 27:1379–1398. doi:10.1002/hyp.9268
- Hébrard, O., M. Voltz, P. Andrieux, and R. Moussa. 2006. Spatio-temporal distribution of soil surface moisture in a heterogeneously farmed Mediterranean catchment. *J. Hydrol.* 329:110–121. doi:10.1016/j.jhydrol.2006.02.012
- Inoubli, N., D. Raclot, I. Mekki, R. Moussa, and Y. Le Bissonnais. 2017. A spatio-temporal multiscale analysis of runoff and erosion in a Mediterranean marly catchment. *Vadose Zone J.* 16(12). doi:10.2136/vzj2017.06.0124
- Inoubli, N., D. Raclot, R. Moussa, H. Habaieb, and Y. Le Bissonnais. 2016. Soil cracking effects on hydrological and erosive processes: A study case in Mediterranean cultivated vertisols. *Hydrol. Processes* 30:4154–4167. doi:10.1002/hyp.10928
- IPCC. 2014. Climate change 2014: Synthesis report. In: R.K. Pachauri and L.A. Meyer, editors, Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change, Core Writing Team. Vol. 151. IPCC, Geneva, Switzerland. https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf (accessed 28 Sept. 2018).
- IUSS Working Group WRB. 2014. World reference base for soil resources 2006. 2nd ed. World Soil Resour. Rep. 106. FAO, Rome.
- Lagacherie, P., J. Álvaro-Fuentes, M. Annabi, M. Bernoux, S. Bouarfa, A. Douaoui, et al. 2018. Managing Mediterranean soil resources under global change: Expected trends and mitigation strategies. *Reg. Environ. Change* 18:663–675. doi:10.1007/s10113-017-1239-9
- Lagacherie, P., M. Rabotin, F. Colin, R. Moussa, and M. Voltz. 2010. Geo-MHYDAS: A landscape discretization tool for distributed hydrological modeling of cultivated areas. *Comput. Geosci.* 36:1021–1032. doi:10.1016/j.cageo.2009.12.005
- Lennartz, B., and X. Louchart. 2007. Effect of drying on the desorption of diuron and terbuthylazine from natural soils. *Environ. Pollut.* 146:180–187. doi:10.1016/j.envpol.2006.04.040
- Lennartz, B., X. Louchart, P. Andrieux, and M. Voltz. 1997. Diuron and simazine losses to runoff water in Mediterranean vineyards. *J. Environ. Qual.* 26:1493–1502. doi:10.2134/jeq1997.00472425002600060007x
- Leonard, J., and P. Andrieux. 1998. Infiltration characteristics of soils in Mediterranean vineyards in southern France. *Catena* 32:209–223. doi:10.1016/S0341-8162(98)00049-6
- Levassasseur, F., J.S. Bailly, P. Lagacherie, F. Colin, and M. Rabotin. 2012. Simulating the effects of spatial configurations of agricultural ditch drainage networks on surface runoff from agricultural catchments. *Hydrol. Processes* 26:3393–3404. doi:10.1002/hyp.8422
- Linde, N., A. Revil, A. Bolève, C. Dagès, J. Castermant, B. Suski, and M. Voltz. 2007. Estimation of the water table throughout a catchment using self-potential and piezometric data in a Bayesian framework. *J. Hydrol.* 334:88–98. doi:10.1016/j.jhydrol.2006.09.027
- Louchart, X., B. Lennartz, and M. Voltz. 2005. Sorption behaviour of diuron under a Mediterranean climate. *Agron. Sustain. Dev.* 25:301–307. doi:10.1051/agro:2005008
- Louchart, X., and M. Voltz. 2007. Aging effects on the availability of herbicides to runoff transfer. *Environ. Sci. Technol.* 41:1137–1144. doi:10.1021/es061186q
- Louchart, X., M. Voltz, P. Andrieux, and R. Moussa. 2001. Herbicide transport to surface waters at field and watershed scales in a Mediterranean vineyard area. *J. Environ. Qual.* 30:982–991. doi:10.2134/jeq2001.303982x
- Louchart, X., M. Voltz, G. Coulouma, and P. Andrieux. 2004. Oryzalin fate and transport in runoff water in Mediterranean vineyards. *Chemosphere* 57:921–930. doi:10.1016/j.chemosphere.2004.07.021
- Ludwig, W., A.F. Bouwman, E. Dumont, and F. Lespinas. 2010. Water and nutrient fluxes from major Mediterranean and Black Sea rivers: Past and future trends and their implications for the basin-scale budgets. *Global Biogeochem. Cycles* 24:GB0A13. doi:10.1029/2009GB003594
- MediTERRA. 2008. Les futurs agricoles et alimentaires en Méditerranée. Ctr. Int. Hautes Études Agron. Méditerranéennes, Presses Sci. Po, Paris.
- Mekki, I., J. Albergel, N. Ben Mechlia, and M. Voltz. 2006. Assessment of overland flow variation and blue water production in a farmed semi-arid water harvesting catchment. *Phys. Chem. Earth* 31:1048–1061. doi:10.1016/j.pce.2006.07.003
- Mekki, I., R. Zitouna-Chebbi, F. Jacob, N. Ben Mechlia, L. Prévot, J. Albergel, and M. Voltz. 2018. Impact of land use on soil water content in a hilly rainfed agrosystem: A case study in the Cap Bon Peninsula, Tunisia. *Agrofor. Int. J.* 3:64–75. doi:10.7251/AGRENG1801064M
- Menon, S., S. Rousseva, N.P. Nikolaidis, P. van Gaans, P. Panagos, D.M. de Souza, et al. 2014. SoilTrEC: A global initiative on critical zone research and integration. *Environ. Sci. Pollut. Res.* 21:3191–3195. doi:10.1007/s11356-013-2346-x
- Milano, M., D. Ruelland, S. Fernandez, A. Dezetter, J. Fabre, E. Servat, et al. 2013. Current state of Mediterranean water resources and future trends under climatic and anthropogenic changes. *Hydrol. Sci. J.* 58:498–518. doi:10.1080/02626667.2013.774458
- Montes, C., J.P. Lhomme, J. Demarty, L. Prévot, and F. Jacob. 2014. A three-source SVAT modeling of evaporation: Application to the seasonal dynamics of a grassed vineyard. *Agric. For. Meteorol.* 191:64–80. doi:10.1016/j.agrformet.2014.02.004
- Moussa, R., M. Voltz, and P. Andrieux. 2002. Effects of the spatial organization of agricultural management on the hydrological behaviour of a farmed catchment during flood events. *Hydrol. Processes* 16:393–412. doi:10.1002/hyp.333
- Pare, N., P. Andrieux, X. Louchart, A. Biarnès, and M. Voltz. 2011. Predicting the spatio-temporal dynamic of soil surface characteristics after tillage. *Soil Tillage Res.* 114:135–145. doi:10.1016/j.still.2011.04.003
- Paroissien, J.B., F. Darboux, A. Couturier, B. Devillers, F. Mouillot, D. Raclot, and Y. Le Bissonnais. 2015. A method for modeling the effects of climate and land use changes on erosion and sustainability of soil in a Mediterranean watershed (Languedoc, France). *J. Environ. Manage.* 150:57–68. doi:10.1016/j.jenvman.2014.10.034
- Raclot, D., and J. Albergel. 2006. Runoff and water erosion modelling using WEPP on a Mediterranean cultivated catchment. *Phys. Chem. Earth* 31:1038–1047. doi:10.1016/j.pce.2006.07.002
- Raclot, D., Y. Le Bissonnais, X. Louchart, P. Andrieux, R. Moussa, and M. Voltz. 2009. Soil tillage and scale effects on erosion from fields to catchment in a Mediterranean vineyard area. *Agric. Ecosyst. Environ.* 134:201–210. doi:10.1016/j.agee.2009.06.019
- Raupach, M.R., and J.J. Finnigan. 1997. The influence of topography on meteorological variables and surface-atmosphere interactions. *J. Hydrol.* 190:182–213. doi:10.1016/S0022-1694(96)03127-7
- Revil, A., D. Hermitte, M. Voltz, R. Moussa, J.G. Lacas, G. Bourrie, and F. Trolard. 2002. Self-potential signals associated with variations of the hydraulic head during an infiltration experiment. *Geophys. Res. Lett.* 29:10-1–10-4. doi:10.1029/2001GL014294
- Ribolzi, O., P. Andrieux, V. Valles, R. Bouzigues, T. Bariac, and M. Voltz. 2000. Contribution of groundwater and overland flows to storm flow generation in a cultivated Mediterranean catchment: Quantification by natural chemical tracing. *J. Hydrol.* 233:241–257. doi:10.1016/S0022-1694(00)00238-9
- Riou, C., P. Pieri, and B. Leclech. 1994. Water-use of grapevines well supplied with water: Simplified expression of transpiration. *Vitis* 33:109–115.
- Saison, C., X. Louchart, M. Schiavon, and M. Voltz. 2010. Evidence of the role of climate control and reversible aging processes in the fate of diuron in a Mediterranean topsoil. *Eur. J. Soil Sci.* 61:576–587.

doi:10.1111/j.1365-2389.2010.01262.x

- Smetanová, A., Y. Le Bissonnais, D. Raclot, J.P. Nunes, F. Licciardello, C. Le Bouteiller, et al. 2018. Temporal variability and time compression of sediment yield in small Mediterranean catchments: Impacts for land and water management. *Soil Use Manage.* doi:10.1111/sum.12437
- Suski, B., A. Revil, K. Titov, P. Konosavsky, M. Voltz, C. Dagès, and O. Huttel. 2006. Monitoring of an infiltration experiment using the self-potential method. *Water Resour. Res.* 42:W08418. doi:10.1029/2005WR004840
- Tassinari, C., P. Lagacherie, R. Bouzigues, and J.P. Legros. 2002. Estimating soil water saturation from morphological soil indicators in a pedologically contrasted Mediterranean region. *Geoderma* 108:225–235. doi:10.1016/S0016-7061(02)00132-5
- Tomer, S.K., A. Al Bitar, M. Sekhar, M. Zribi, S. Bandyopadhyay, K. Sreelash, et al. 2015. Retrieval and multi-scale validation of soil moisture from multi-temporal SAR data in a semi-arid tropical region. *Remote Sens.* 7:8128–8153. doi:10.3390/rs70608128
- Trambouze, W., P. Bertuzzi, and M. Voltz. 1998. Comparison of methods for estimating actual evapotranspiration in a row-cropped vineyard. *Agric. For. Meteorol.* 91:193–208. doi:10.1016/S0168-1923(98)00072-0
- Trambouze, W., and M. Voltz. 2001. Measurement and modelling of the transpiration of a Mediterranean vineyard. *Agric. For. Meteorol.* 107:153–166. doi:10.1016/S0168-1923(00)00226-4
- Voltz, M., and A. Albergel. 2002. OMERE: Observatoire Méditerranéen de l'Environnement Rural et de l'Eau- Impact des actions anthropiques sur les transferts de masse dans les hydrosystèmes méditerranéens ruraux. Proposition d'Observatoire de Recherche en Environnement. Minist. Français Rech., Paris.
- Voltz, M., W. Ludwig, C. Leduc, and S. Bouarfa. 2018. Mediterranean land surfaces under global change: Current state and future challenges. *Reg. Environ. Change* 18:619–622. doi:10.1007/s10113-018-1295-9
- Voltz, M., I. Mekki, J. Molénat, L. Prévot, D. Raclot, and R. Zitouna-Chebbi. 2016. Long term agro-system observatories in the Mediterranean. In: M.-L. Sabrié, et al., editors, *The Mediterranean region under climate change: A scientific update*. Inst. Rech. Dév., Marseille, France. p. 465–475.
- Wassenaar, T., P. Andrieux, F. Baret, and J.M. Robbez-Masson. 2005. Soil surface infiltration capacity classification based on the bi-directional reflectance distribution function sampled by aerial photographs: The case of vineyards in a Mediterranean area. *Catena* 62:94–110. doi:10.1016/j.catena.2005.05.004
- Wezel, A., S. Bellon, T. Doré, C. Francis, D. Vallod, and C. David. 2009. Agroecology as a science, a movement and a practice: A review. *Agron. Sustain. Dev.* 29:503–515. doi:10.1051/agro/2009004
- Zitouna-Chebbi, R. 2009. Observations et caractérisation des échanges d'eau et d'énergie dans le continuum sol-plante-atmosphère en condition de relief collinaire. Cas du bassin versant Kamech, Cap Bon, Tunisie. Ph.D. diss., Univ. Montpellier, Montpellier, France.
- Zitouna-Chebbi, R., L. Prévot, A. Chakhar, M. Marniche-Ben Abdallah, and F. Jacob. 2018. Observing actual evapotranspiration from flux tower eddy covariance measurements within a hilly watershed: Case study of the Kamech site, Cap Bon Peninsula, Tunisia. *Atmosphere* 9:68. doi:10.3390/atmos9020068
- Zitouna-Chebbi, R., L. Prévot, F. Jacob, R. Mougou, and M. Voltz. 2012. Assessing the consistency of eddy covariance measurements under conditions of sloping topography within a hilly agricultural catchment. *Agric. For. Meteorol.* 164:123–135. doi:10.1016/j.agrformet.2012.05.010
- Zitouna-Chebbi, R., L. Prévot, F. Jacob, and M. Voltz. 2015. Accounting for vegetation height and wind direction to correct eddy covariance measurements of energy fluxes over hilly crop fields. *J. Geophys. Res., D, Atmospheres* 120:4920–4936. doi:10.1002/2014JD022999